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ABSTRACT

Provided is a collection of papers on computer literacy and simulation originally published in The Physiology Teacher, supplemented by additional papers and a glossary of terms relevant to the field. The 12 papers are presented in five sections. An affirmation of conventional physiology laboratory exercises, coping with computer terminology, and an overview of computer hardware are considered in the three papers in section 1 (introduction). A primer on computer technology and discussion of the analog computer as a physiology adjunct are presented in the two papers in section 2. A single paper in section 3 focuses on the rationale for and resources utilized in teaching computer literacy and physiological simulation, and includes descriptions of simulation programs. State of the art with regard to physiological simulation is considered in the five papers presented in section 4. Topics/areas addressed include carbon dioxide control in respiratory systems simulation, teaching simulation with microcomputers, computer model of cardiovascular system for effective learning, computer simulation in the student laboratory, and digital computer simulation of cardiovascular and renal physiology. Advantages and limitations of physiological simulation are considered in the final paper presented in section 5. (JN)

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Frontiers in the Teaching of Physiology

Computer Literacy and Simulation

Edited by

Charles S. Tidball, Ph.D., M.D.
M. C. Shelesnyak, Ph.D.

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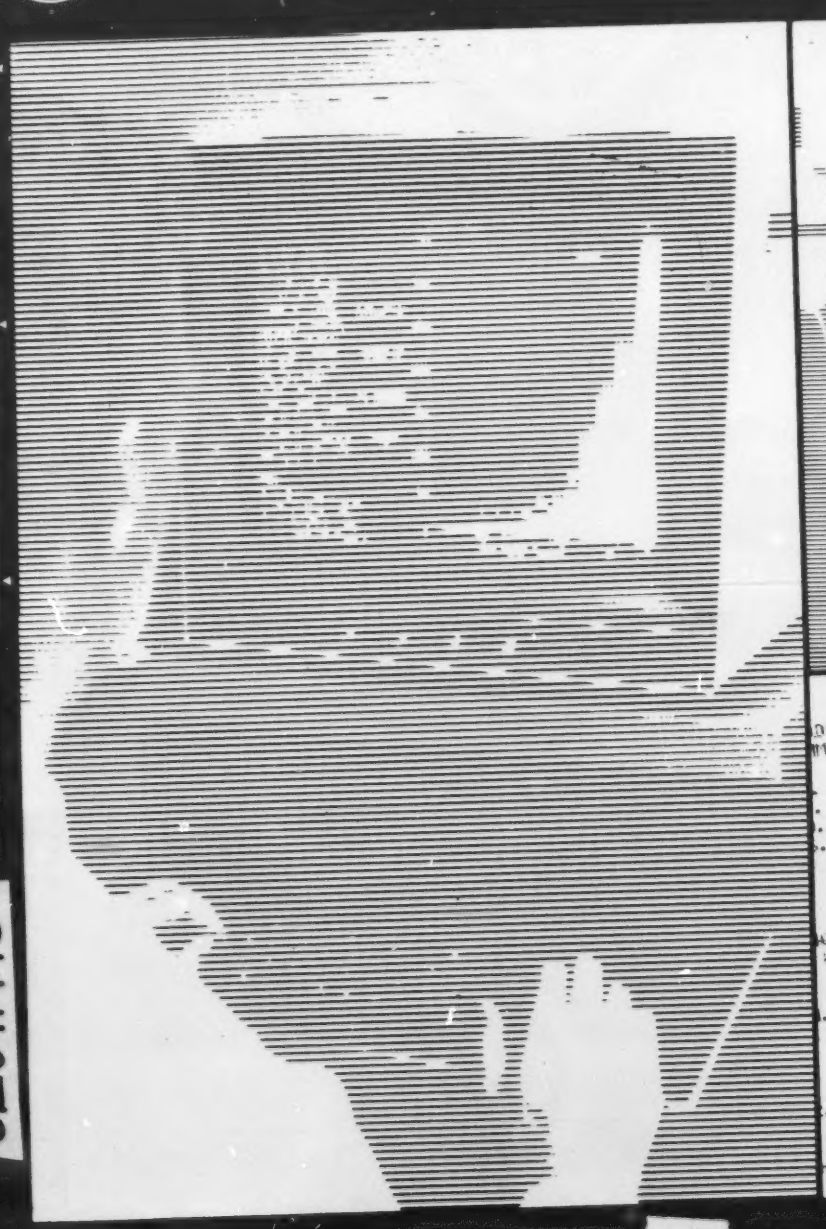

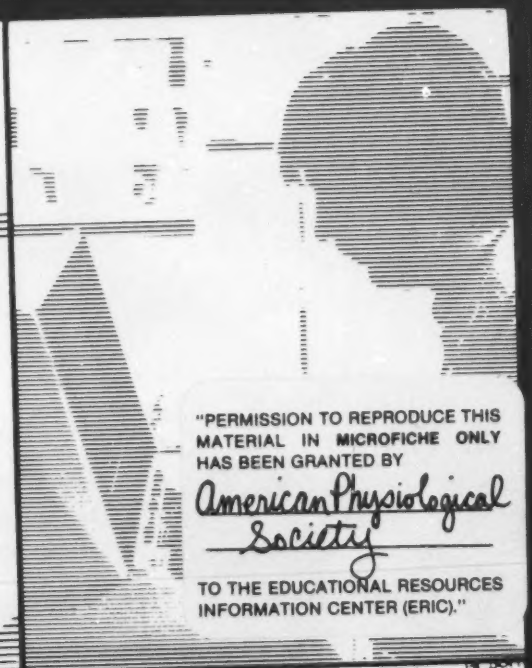

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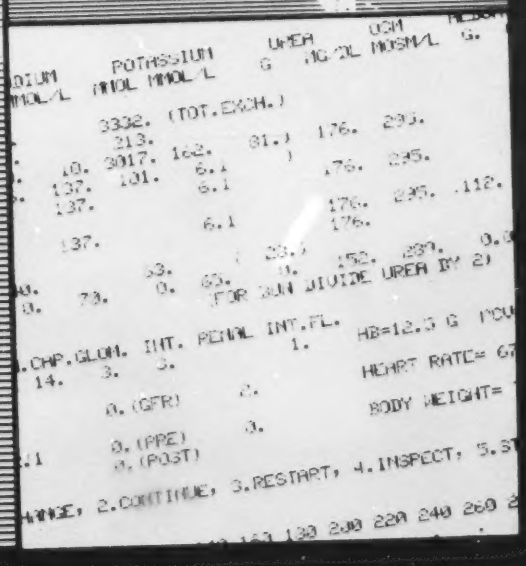

FRONTIERS IN THE TEACHING OF PHYSIOLOGY: COMPUTER LITERACY AND SIMULATION

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PREFACE

An expression of the state of the art with regard to physiological simulation, a series of articles, was started in *The Physiology Teacher* section of Volume 21, Number 6 of *The Physiologist,* under the editorship of Dr. Charles S. Tidball. As the series developed and some other material appeared in *The Physiology Teacher,* it became clear that issuing a reprint of the collected papers with some additional articles and a glossary of terms relevant to the field was warranted. This volume is the product of the original articles, the added matrix material, and some thoughts on the general subject of computers and laboratory teaching.

Generation of this collection has also stimulated a plan to consider development of other "reprint-series" on various teaching (and historical) subjects. Precedence for reprinting collected papers from *The Physiologist* was made in 1973. Interestingly, the subject was "Computer Assisted Education" and Dr. Tidball played a leading role (1). This collection of articles initiates a new series which we plan to pursue on the general subject of physiology teaching. It has also stimulated some contemplation on current problems associated with the teaching of physiology to future physiologists who will engage in teaching and research, and to medical students who will a) practice medicine or b) engage in medical research or c) undertake both.

The collection begins and ends with expressions of concern: "An Affirmation of Conventional Physiology Laboratory Exercises," and "Physiological Simulation: An Assessment of its Advantages as Well as its Limitations." It is useful to begin framing the problem of teaching physiology within the alarming trend of curricular changes revealed in an important study reported in 1972 in *The Physiologist* by Maurice Visscher on "The Decline in Emphasis on Basic Medical Sciences in Medical School Curricula" (2). Visscher reported that basic physiological instruction in 108 medical schools which submitted data for 1971-1972 ranged widely (60-360 hours) with a mean number of assigned hours of 159; data from 74 schools in operation ten years earlier was 246 hours (range of 100-440). (These same 74 schools reduced the hours by 1971-1972 to a mean of 170).

The most alarming tendency, as I see it, was the fact that in 1971-1972, 10 medical schools had no assigned student laboratory work in physiology and 25% had none assigned in pharmacology (3). Over the ten-year period, 1962-1972, in the 74 schools referred to above, none *increased* curriculum hours and all but 13 reduced assigned laboratory time by 75-250 hours. Dr. Visscher's analysis reveals the complex bases for this deterioration: increased costs of animals, premium on physical space, disinterest of students in laboratory work, and regrettably even a growing disinterest of teachers.

In part, the advent and rapid development in computer assisted instruction, and more specifically computers for physiological simulation have repaired some of the damage caused by the reduction in assigned hours of laboratory instruction. The effectiveness of physiological computer simulation has been established for some time, but simulation has been limited in its use because of costs. The availability of microcomputers at reduced costs will make use of physiological computer simulations more commonplace.

"... physiologists who have practiced computer simulation of physiological mechanisms, without exception, do not have to be sold on its importance. Yet, it is difficult to portray to the uninitiated the satisfaction that comes from fitting together the basic pieces of a physiological mechanism, and then making the total system function as an integral unit. It is hard to tell the non-believer that many of the simplest mechanisms that we have taught for years do not in reality function exactly as our intuitions have led us to believe. Yet, when one sees the computer solutions of function under both normal and abnormal conditions, one is often led into new logical dimensions and certainly to a fuller understanding of basic physiology" (4).

"Simulation means calculating the response of a model by substituting values for its parameters, and a range of values of the independent variables. It is thus possible to investigate the characteristics of the model under a variety of conditions. The behavior of the real system can, of course, be studied only by experimentation" (5). It is therefore not the romantic in me that urges every effort be made to avoid the flight from the warm laboratory; from animal experimentation in teaching physiology.

Our concern with teaching turns us back to two very great teachers in America, Louis Agassiz at Harvard, and William Osler at Johns Hopkins. Agassiz believed that above all, a scientist is a person who sees things other persons miss. He admonished us to "study nature not books." Thus he trained his laboratory students by his painstaking, demanding, and relentless insistence, to *see.* And it was Osler who introduced the technic of teaching medicine by using patients as texts. The computer can be a great adjunct to learning but it must not become a replacement either for the living subject or the patient.

We hope this small collection of papers will be useful in the appreciation of not only the computer but also the experimental models and the living organisms on which we must base the teaching of physiology.

M. C. Shelesnyak, Ph.D.

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Contents

List of Contributors iv

SECTION ONE – Introduction

Chapter

1. An Affirmation of Conventional Physiology Laboratory Exercises - C. S. Tidball 1
2. Coping with Computer Terminology - C. S. Tidball 2
3. An Overview of Computer Hardware - C. S. Tidball 4

SECTION TWO – How Computers Work

4. Doctors, Digits and Disks - C. S. Tidball 7
5. The Analog (Computer) as a Physiology Adjunct; Part 1 - P.A. Stewart 12

SECTION THREE – Use of Computers in the Physiology Laboratory

6. Teaching Computer literacy and physiological Simulation - C. S. Tidball 15

SECTION FOUR – State of the Art with Regard to Physiological Simulation

7. The Analog (Computer) as a Physiology Adjunct; Part 2 - P. A. Stewart 21
8. Teaching by Simulation with Personal Computers - J. E. Randall 23
9. A. Computer Model of the Cardiovascular System for Effective Learning -C. F. Rothe 27
10. Computer Simulation in the Physiology Student Laboratory - S. Katz, R. G. Hollingsworth, J. G. Blackburn, and H. T. Carter 33
11. A Digital Computer Simulation of Cardiovascular and Renal Physiology -C. S. Tidball 37

SECTION FIVE– Some Cautions with Regard to Physiological Simulation

12. Physiological Simulation: an Assessment of its Advantages as well as its Limitations - R. A. Standing and C. S. Tidball 43

Glossary - C. S. Tidball 47

Bibliography 56

Index 57

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SECTION ONE - INTRODUCTION

Chapter One

AN AFFIRMATION OF CONVENTIONAL PHYSIOLOGY LABORATORY EXERCISES

Charles S. Tidball

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This assessment of the state-of-the-art with regard to physiological simulation would be incomplete without a clear statement of the importance of conventional physiology laboratory exercises involving living material. Today, many medical schools are decreasing the number of hours of required laboratory work associated with their medical and graduate student physiology courses. Many reasons are offered for this change: a) many students have already performed classical physiology experiments prior to entering medical school, b) curricular reorganization has encroached on the time available, c) successful laboratory teaching must be done in small groups and thus requires an extensive commitment of faculty time, d) equipment for such teaching has become increasingly sophisticated and therefore expensive, e) the cost of laboratory animals, especially the larger mammals, has become prohibitive at a time when medical schools are facing severe pressures for cost containment, and f) recent federal regulations with regard to human experimentation place new burdens on those who would use students as experimental subjects. All these reasons have some measure of validity, but my purpose is not to catalog constraints. Rather, I desire to restate the case for physiology laboratory exercises and thus help us to resist those forces which cause us to reduce our commitment to effective laboratory teaching.

An Opportunity to Discuss the Ethics of Medical Research

As practitioners of the basic medical sciences we have a responsibility to foster the professionalization of young people who come to us for advanced training. One of the societal misconceptions supported by media dramatizations is that scientists are dispassionate and that their desire to obtain knowledge provides them with a rationalization to exceed the bounds of propriety with regard to the treatment of experimental animals. The best way to combat these erroneous views is for us to offer laboratory exercises in which we behave as exemplary humanitarians as we handle experimental animals and living tissue derived from them. This is particularly important as it pertains to anesthetizing large animals. Too often that crucial activity is left in the hands of those who are not well-trained and who have little sense for the reverence of life. Thus, if a dog or cat is delivered to the teaching laboratory so lightly anesthetized that the animal re-enters the excitement stage, a very poor impression is made on students who do not yet appreciate that reflex movements and cries do not orginate from a conscious level. Similarly, an animal that has received too much anesthetic must immediately be placed on a respirator which creates a mechanical substitute for a physiologic process and is a less than ideal situation.

The professionalization of the student involves an understanding of what can best be learned from lectures and textbooks and what requires exposure to the living material. The justification for the use of animals in drug testing and other forms of medical reseach should be developed. Yes, we can use computer support to undertake some of this teaching, but I do not believe the simulations will carry as much impact with regard to the ethics of medical research as the presence of a live animal in an appropriately designed laboratory exercise where the faculty demonstrate a high degree of awareness for humanitarian considerations.

An Opportunity to Observe the Unique Characteristics of Living Material

Just as every human being is unique, that principle applies to lower forms of life: no two animals will behave in exactly the same manner. Though possible through creative programming, it is more difficult to create uniqueness in a simulation than it is to reach into the living world where it is a given. Students of the health professions tend to think of experimental animals as patients and will have a genuine sense of loss if the animal succumbs before the laboratory is completed. The fragile thread of life can be broken without much warning, especially for those who are not yet trained in reading signs of decompensation. Equally important lessons are available while the animal still live: the presence of a blood supply and resilient tissues which have not been hardened or discolored by the embalming process; the redundancy of physiological mechanisms where several processes carry on the same function to assure its proper performance; the amount of abuse that living material can absorb before reaching an irreversible state; the relationship between

stimulus and response and those limits where a further small increase in stimulus brings about an entirely different response. Since life *is* the stuff with which the student eventually must deal, there is no substitute for providing supervised experiences where this learning can take place effectively.

An Opportunity to Deal with Biological Variation

In an earlier era, much of the biostatistics relevant to the practice of medicine could be derived from the techniques used to treat biological data emanating from physiology laboratory exercises. Today we have special courses in statistics which approach the subject from a theoretical point of view and are more likely to deal with population parameters rather than individual variation. Yet each person who is to be responsible for prescribing medication, and we have today treatment modalities much more powerful than those of an earlier time, must ultimately develop a sense of posology. To me, it is better to develop this skill on an anesthetized animal than to have to learn it at the expense of the first few patients that a new physician begins to treat.

Similarly, having attempted to perform chemical analyses on blood and urine in the physiology laboratory creates a proper degree of skepticism in the would-be physician with regard to the validity of clinical laboratory data. As miniaturization and automation alter the clinical laboratory, an aura of mystery shrouds how it is possible to obtain so much information from such a small sample. The fundamentals of sampling technique are often ignored and failure to protect specimens as they are transported from patient to laboratory exact a toll of misinformation. Some of these obligate sources of error seem to recede when the final results are presented in an authoritative format which clearly shows the validity of the analysis as compared with interspersed standards.

An Opportunity to Expose the Student to Medical Procedures

We should not omit from this discussion those physiology exercises in which a student is used as the experimental subject. Here is an important setting for the embryo physician to voice concerns which any patient might have when first exposed to electronic monitoring or other recording procedures. How often will students make inappropriate jests about electrocution at the expense of the subject who has been fitted with electrodes for electrocardiography? When a student has been subjected to the discomfort of an insufficiently deflated sphygmomanometer cuff s/he will be more careful when it is her/his turn to make a blood pressure measurement.

Much of the practice of medicine deals with specimens derived from blood, urine, feces and other body fluids. When the latter must be obtained at some discomfort to the patient, it is instructive for the physicians of tomorrow to be familiar with these procedures as a result of personal experience. This is not to suggest that swallowing a gastric tube should be required in the absence of a person who can assist the student in avoiding a vomiting response. The important point is that exposure to medical procedures and the development of professional attitudes regarding how to handle patient anxiety, how to perform simple clinical measurements, and how to collect, store, and analyze specimens derived from humans are all worthwhile by-products of the physiology teaching laboratory.

Finally, it should be recalled that physiology, an amalgamation of *physics* and *biology,* is a science deeply rooted in the experimental method. To teach physiology as a description of facts, without providing each student a personal context of the methods used to develop this body of knowledge, is at best to rob it of its vitality; at worst, such teaching is a travesty on those whose learning has been intrusted to our care.

Chapter Two

COPING WITH COMPUTER TERMINOLOGY

Charles S. Tidball

Computer science, like other disciplines, has evolved a language of its own. Some of this development consists of words in general use which have taken on restricted meanings when used in a computer related context; more often, totally new expressions have emerged. Many of the new terms are acronyms which means pronounceable words formed from the letters of other words, for example: FORTRAN, the name of a computer language which accomplishes mathematical FORmula TRANslations; other terms consist of the initial letters of compound terms, for example: TV which is easier to say than TeleVision, or CRT than Cathode Ray Tube. In order to enable persons approaching the subject for the first time to acquire a sense for computer terminology as rapidly as possible, a Glossary has been developed. Many of the definitions in the Glossary contain other terms from the Glossary in context. The terms most frequently used are considered a Basic Vocabulary and are presented in the three paragraphs which follow. These are the terms printed in bold-faced type; it should be possible to derive their meaning from the way they are used in the paragraphs. Definitions for these terms are also contained in the Glossary at the back of the volume.

Computers are machines which have been designed to perform complex tasks with a minimum of human intervention. Because of their speed, their retention power, and their ability to perform tasks like human beings, computers are occasionally personified; but it should be emphasized that they remain machines. There are two general varieties of computers: **analog** and **digital. Analog** computers utilize continuously variable physical quantities, such as electrical voltages and different electronic units, to represent the elements in a problem to be solved. The process of measurement is used to arrive at a final answer which can often be read directly from a meter or other **analog** device. By contrast, **digital** computers utilize **binary,** a discontinuous numerical system consisting only of zeros and ones, to represent the elements in a problem. The way in which the numbers must be manipulated to arrive at a solution is **program-**

med into the machine and the process of counting is used to obtain intermediate and final answers. Both **analog** and **digital** computers have been used to solve problems of interest to physiologists; but when the word computer is used without a modifier, it generally refers to a **digital** computer.

An important distinction is made between that part of a computer physically present as equipment, referred to as **hardware,** and that part of a computer representing **instructions** to the equipment and designated **software.** Major subdivisions of each of these parts are recognized. **Hardware** exists either as a central processing unit, called **CPU** for short, or as **peripheral devices.** The **CPU** contains elements which keep track of what the computer is doing, store intermediate results, and perform calculations. Some of the storage is done in the **CPU** in electronic units called **memory** which can be **accessed** very quickly. Less expensive retention, with somewhat slower retrieval capabilities, is contained in **peripheral devices** known as **mass storage units.** Another example of a **peripheral device** is a computer **terminal** which consists of a keyboard and a display device similar to a television screen. A **terminal** may be used either to **access** data which are stored in the computer or to generate **instructions** to the computer, a process known as **programming.** Because of miniaturization and advances in electronics, a complete **microcomputer** can now be contained in the same space as a portable television set.

Software exists in three main categories: **operating systems, computer languages,** and **application programs. Operating systems** contain utilities which automatically perform repetitive tasks that would be tedious for a human operator to undertake. In some instances because computers are able to **execute** millions of **instructions** per second, human operators would be unable to accomplish system tasks rapidly enough to insure satisfactory computer utilization. Therefore, **computer languages** have been developed to improve the communication between human beings and these machines. For reliability and to maintain high operational speed the internal manipulations of computers are carried out in a **binary** language, consisting only of zeros and ones. Some **computer languages** are close to **binary** language but the so-called **high-level languages** have been designed to facilitate **programming** the solution of different kinds of **computer applications.** An **application program,** such as the **instructions** to generate a payroll, is the specific solution to a **computer application** as it has been **programmed** in the most appropriate **computer language.** Just as one does not need to know how to build an automobile in order to drive it, the user of a computer does not need to know how **programming** is accomplished or how the different elements of **software** collaborate to make computer utilization efficient. Because of the multiplicity of intricate tasks performed, especially for larger and more complex **computer applications, programming** has become a substantive intellectual activity.

This completes the presentation of the Basic Vocabulary which has introduced you to twenty terms. A summary of these concepts and a complete listing of the Basic Vocabulary in alphabetical order is provided below. For those interested in the techniques used to develop the Glossary and the Basic Vocabulary, a description is provided in an Appendix to the Glossary along with a few references to other sources of computer definitions.

SUMMARY

Two kinds of computers: **analog** and **digital**

Two parts of a digital computer: **hardware** and **software**

Two subdivisions of hardware: **CPU** and **peripheral devices**

Two kinds of retrieval units: **memory** (fast but expensive) and **mass storage** (of larger capacity and capable of being removed from the machine)

Three kinds of software: **operating systems, computer languages** and **application programs**

Two kinds of computer languages: **binary** (the machine's own language) and **high-level languages** (optimized for undertaking specific human tasks)

Two tasks which can be **executed** on computers: **access** to data stored in the computer and **programming** (generating **instructions** to the machine for the solution of a **computer application**)

Two different units that look similar: **terminal** (a **peripheral device** which must be connected to the computer to perform useful work) and **microcomputer** (a small, full-capability, **digital** computer)

ALPHABETICAL LIST OF TERMS IN BASIC VOCABULARY

(The terms in the Basic Vocabulary are used so frequently in the Glossary definitions that it will be a distinct advantage to readers to master this list of terms before attempting to use the Glossary.)

access
analog
application program
binary
computer application
computer language
CPU
digital
execution
hardware
high-level language
instruction
mass storage
memory
microcomputer
operating system
peripheral device
programming
software
terminal

OVERVIEW OF COMPUTER HARDWARE

Charles S. Tidball

The development of the digital computer has stimulated one of the more dramatic growth industries known. This however would not have been possible without an equally impressive development in electronics technology. It is not easy to describe briefly these two rapidly moving developments which have brought about The Age of Technology. At the insistence of my co-editor, I have made the attempt, with an apology at the outset, to readers involved in this development and who may have preferred a different presentation.

The first modern computer, the Mark I, was developed at Harvard University starting in 1939. It took five years to assemble and was physically quite bulky. Because the electromagnetic relay was the basis for storing information, calculations were slow and power requirements were substantial (1). A successor, the ENIAC, built at the University of Pennsylvania utilized the vacuum tube as a storage and switching device and became the first electronic computer. It was developed in only three years because of military urgency and a perceived need for such a computational device by the Services. The vacuum tube acted so much faster than the electromagnetic relay that ENIAC could perform computations about a thousand times more rapidly. However, this machine was limited because it took several people several days to set up a problem for calculation. This process involved making hundreds of wired connections (2). The next stage in the development was the ability to store the instructions to the machine in the computer's memory and to obviate the complex set up procedure. Such machines included the first commercial stored-program computer built by Sperry-Rand, UNIVAC, and were put in operation in the early 1950's (1).

Two other features were crucial to the rapid development and improvement of this technology. The first of these was the introduction of binary number representation; and the second was increasing miniaturization of electronic components. Numerical representation is discussed in Chapter Four. Miniaturization made possible significant advances because it permitted simplicity of design, increased speed of operation, and decreased power requirements with subsequent reduction in heat generation. This progress in electronics which led from the vacuum tube, to the transistor, to the integrated circuit, and now to large scale integration, or LSI technology, has brought spectacular improvements in cost, speed, and size of storge in less than 30 years. The following tabulation, based on IBM products (3), dramatically reveals these improvements.

TABLE I

Year	Model	Cost*	Speed+	Storage#
1952	701	$221,867	2,193	400
1959	1401	105,600	4,166	100
1964	360	28,800	12,000	8
1976	370	3,800	43,000	0.3
1979	4341	430	239,120	0.03

* Rental cost per month for one megabyte of storage
\+ Processor speed in multiplications per second
\# Number of cubic feet required for one megabyte of storage

There are many different kinds of computers. The range encompasses the smallest units which are used in wrist watches to the so-called super computers that may cost tens of millions of dollars. In addition to cost and space requirements there are various convenient measures of computer size which enable certain distinctions to be made. One of these is memory capacity. Another, more fundamental measure, is the length of the computer word. Most computers have a fixed word length which means that the registers in the machine and the individual locations in memory can only store as many items, (called bits), of binary information as the length of the computer word in that particular computer. Smaller, less powerful, computers tend to have shorter computer words. The extent of memory and mass storage can also be used to describe the size of a computer. Memory and mass storage are measured in bytes. The standard byte contains 8 bits; and since this is usually the amount of information needed to code a number or a letter, the term byte can be equated to character. Using information from Weitzman (4) and other sources, the following table has been derived to show the interrelationships among some of these variables.

TABLE 2

Verbal Description	Number of Bits in Computer Word	Number of Bytes* of Memory	Number of Megabytes of Mass Storage	Approximate Cost
Microcomputer	4 - 8	4K - 64K	1	< $10,000
Minicomputer	12 - 24	32K - 256K	10	$ 10,000 - 100,000
Midicomputer	16 - 36	64K - 1.2M	100	$100,000 - 1,000,000
Mexicomputer	32 - 60	> 0.5M	1,000	> $1,000,000

* The letters K and M are used to designate thousands of bytes or millions of bytes (megabytes) respectively

The table above should be taken only as an approximation because development is proceeding so rapidly that the microcomputer of tomorrow will have more power and speed than the minicomputers of only a few years ago, and this will be accomplished at continuing decreases in hardware cost. Regrettably, the costs of using computers, which are inherently personnel costs, are growing steadily as more diverse ways are found to make these machines useful to society and as increasing specialization occurs in the various categories of jobs that have been created by this developing industry.

It would be appropriate to characterize ways in which computers are used. Initially, computers were used to compute ballistic trajectories; and later, simple scientific and business-oriented problems. To maximize machine efficiency these jobs were submitted in a sequential batch mode, a technique of data processing which has come to be known as batch-processing. In this style of computing, the job resides in the machine only as long as it is necessary to perform the computations and generate

the desired output. An alternative approach permits a number of users to appear to have simultaneous access to the machine and is designated time-sharing. The latter is especially useful for those categories of computing which require frequent consultation with data or programs stored in the computer. The advent of smaller, less expensive machines occasionally blurs the distinctions between batch-processing and time-sharing. It is possible to indicate the growth in complexity of computer applications in graphic form. Figure 1 is reprinted from Weitzman (4) by permission. As one goes from the center of the figure outward, one encounters the subdivisions of machine operation, and, eventually in the outer circle, the multiplicity of computer applications which are possible under each subdivision. For further details about this figure consult the original source (4).

skills are not essential, there are techniques which must be mastered. These include logging-on to the system, gaining access to certain files stored in the computer, correcting errors before they are processed by the computer, and causing the results to appear at the output device in a useful format. Generally, these are the techniques that one uses to communicate with asynchronous multi-program systems operating under time-sharing, but they are not very different from the skills used in obtaining services from the smaller, single-user microcomputers. As far as physiological simulation is concerned, it too can be done on a variety of machines including, in some instances, batch-processing approaches. However, here also time-sharing computers of various sizes as well as stand-alone microcomputers are the machines most likely to be used in the teaching of students.

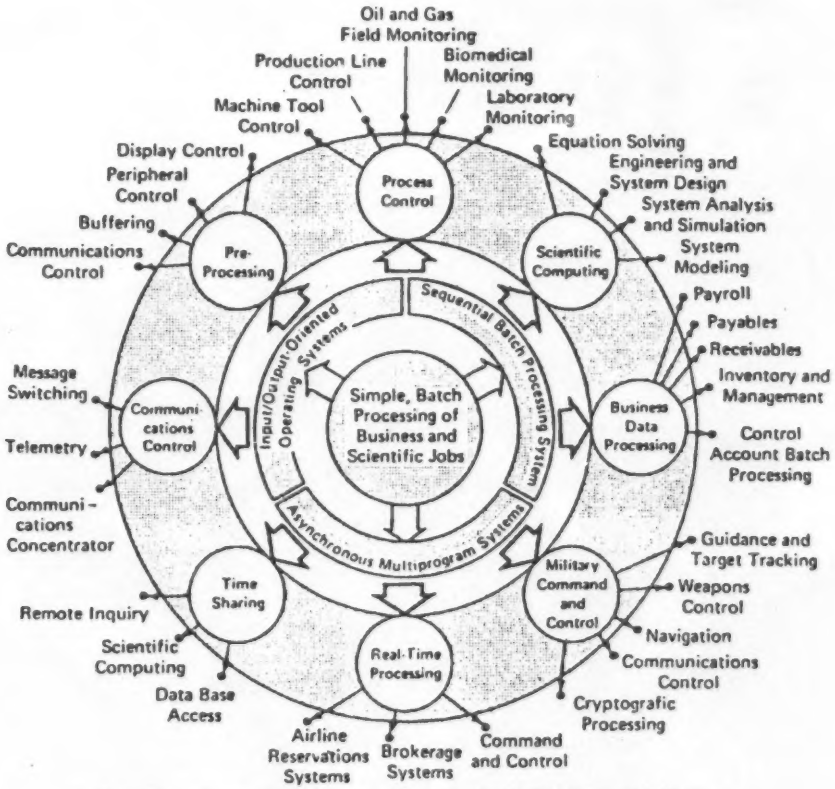

Figure 1 Computer systems application development, starting from sequential batch processing of business and scientific jobs, grew from sequential, asynchronous multiprogramming and I/O-oriented operating systems into time sharing, real-time processing, process control, communications, and several other types of computing systems

Cay Weitzman, *Minicomputer Systems*, 1974, pp. 7. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Finall,, it would be worthwhile to comment on which type of computer is appropriate for teaching computer literacy and demonstrating physiological simulation. There is some choice because computers are sufficiently versatile that more than one type of machine can be used to deal with these applications. As developed in this volume, computer literacy refers primarily to the way one communicates with a computer by means of the key board of the conventional computer terminal. Although typing

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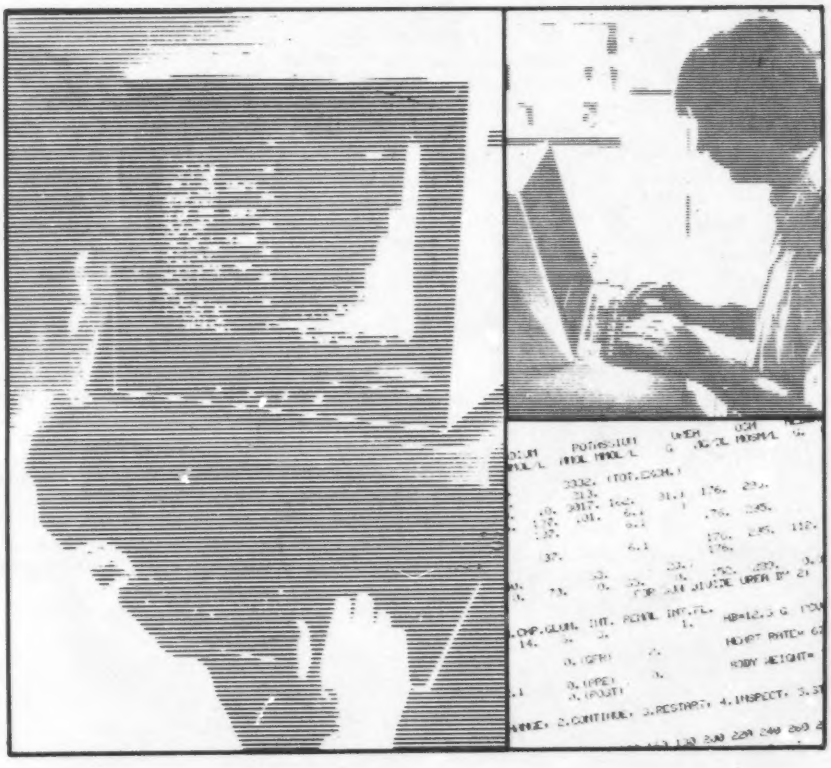

SECTION TWO – HOW COMPUTERS WORK

Chapter Four

DOCTORS, DIGITS AND DISKS: A PRIMER ON COMPUTER TECHNOLOGY*

Charles S. Tidball

Introduction

Lest any should be confused by the title, this communication is *not* directed only at hand surgeons or othopods. It deals with the implications of computer technology on medicine and is commended to every physician, regardless of the nature of his or her practice. Man tends to be threatened by that which he does not understand. Nowhere is this more clearly evident than in the reaction of many physicians to the impending computer technology which promises to change the practice of medicine much as it has already altered our concepts of what is possible and impossible in such disparate fields as motel reservations, manned-space flight; and medical infromation retrieval.

Let us illustrate the scope of the problem by discussing a commonly held misconception: namely, that computers are impersonal and dehumanizing. This assertion is paradoxic because one of the advantages of computer technology is the ability to render a specific service to an individual at a high level of precision and with considerable speed. The belief comes about because many of our transactions with machines are based on numbers rather than names, which evolved because computers were originally designed to function with numbers. When they are made to process letters, these have first to be changed to numbers for the benefits of the machine and then changed back into letters for the final application; to minimize the number and extent of such conversions, the people who first programmed computers substituted multi-digit numbers for names. Thus it is not computers which are impersonal and dehumanizing, but the people who program them and the administrators who determine how many refinements will be permitted in a particular program. Unfortunately, this adds only to the ageless evidence that man is still his own worst enemy.

A second important point is an appreciation of what computers can and cannot do in the field of medicine. A computer can be programmed to interview a patient; it can do so with greater thoroughness than some physicians, especially if the latter are distracted or in too big a hurry. A computer can be programmed to read and interpret an electrocardiogram; it can do so with greater uniformity than individual interpreters at a heart station, but it still has trouble identifying certain disturbances of rhythm. A computer can be programmed to store medical records in random access disk files where they can be interrogated so that information retrieval becomes efficient and accurate. But, computers cannot be programmed to substitute for informed medical judgment. We need not be threatened by these devices. They have been designed by mortal men to assist us in the important work we perform. They are only the latest in an armamentarium of technological adjuncts which improve the ability of the physician to accomplish his or her appointed tasks.

Before we can make full utilization of this new equipment, however, we must learn under what circumstances the often extensive financial investment associated with access to these devices has the best chances of being successful. To that end, this primer on computer fundamentals is offered.

The Speed of the Digital Computer

An adding machine or a rotary calculator performs arithmetic at speeds analogous to that of a human being. Thus person who are unusually gifted may perform calculations mentally and keep up with these machines, if the numbers are not too large. By contrast, the speed of even the earliest digital computers exceeded human capacities. Since then we have gone through four generations of computer design. Electro-magnetic relays were replaced by vacuum tubes which gave way to transistors and were themselves superseded by integrated circuits. Each of these substitutions yielded improvments with regard to speed, so that today the duration of a single cycle of machine operation is measured in nanoseconds, the one billionth part of a second. It is diffiult for the human mind to comprehend that a man-made machine can actually carry out many millions of steps within a single second.

The Precision of the Digital Computer

Two factors make the computer very precise in its operation with numbers. It is capable of dealing with very large numbers without having to round them off to smaller numbers during the course of a calculation. The process of rounding off which is used in manual calculation is one of the principle sources of error in the final answer. Secondly, large computers have a checking quantity known as parity, which provides an internal safeguard against an incorrect transfer of a number from one portion of the system to another. If the parity check is not fulfilled, the computer automatically copies the number again until a proper parity tally is obtained. Thus the degree of error in a modern computer is generally less than one part in a million.

The Storage Capability of the Digital Computer

Unlike human memory, storage in the computer is positive and permanent. When this is coupled with a large potential size of storage, depending on the individual computer and its intended use, we arrive at one of the reasons why it is difficult for human beings to understand computer capabilities. Digital computers have several different levels of memory depending on how rapidly the information must be made available: the main memory, which is often called core memory because it is made up of ferro-

*Although this paper was published in 1973 in the *Medical Annals of the District of Columbia,* Vol. 42, No. 10, pp. 473-479 which is no longer being published, the substance is considered highly appropriate for inclusion in this collection of reprints. M.C.S.

magnetic beads or cores; disk memory, which consists of spinning platters with surfaces that can be specifically magnetized; and tape memory where the information is stored on magnetic tape that can be reeled from place to place automatically by the computer. The main memory is the fastest and also the most expensive. It has the disadvantage that the information cannot be removed from the computer without first transferring it to another form of memory. The disk memory, although several orders of magnitude slower than core memory, can store large amounts of information at reduced cost. In both core and disk memory the information is said to be randomly accessible because any indivdual item can be retrieved without first having to sort through a large number of other items. Tape memory is not randomly accessible and is very slow compared to disk memory, but it has the advantage of being a convenient way to store information outside the computer in a form which permits easy re-entry as desired.

Information Representation in the Digital Computer

The modern digital computer is inherently a simple counting device. In order to satisfy engineering requirements of speed, simplicity, and reliability, the counting is done with elements that are only capable of two states. Although various terms have been used to express these states depending on the frame of reference, ultimately the representations 0 and 1 are used to designate the state of the counting elements. Since only two states are possible, we say that numerical representation in the machine is binary. This is an important point to appreciate: the only language the machine can understand is a language whose entire alphabet is comprised of the two characters 0 and 1.

Just as in ordinary language we tend to group letters into words, so in computer language the zeroes and the ones are grouped into words with one important difference. For a given model of computer, every word is the same length as every other word. The number of characters in a computer word is often referred to as the number of bits. Thus to say that a computer has a 16 bit word, means that the zeroes and ones are grouped 16 at a time for processing by the machine. Occasionally, especially with computers that have a large number of bits per word, the term byte is used to designate a subdivision of the word: 32 bit words are often subdivided into bytes each of which contains 8 bits. The use of the concept byte is also related to storing letters in the computer since 8 bits are generally required to designate one ordinary letter, numeral or punctuation mark.

Even when clusters of zeroes and ones are broken up into words or bytes, they are unintelligible to the average human being. Therefore numeric representations of sequences of zeroes and ones have been used to help practitioners of computer technology grasp what information or instruction is being stored in a particular register of the machine at any given time. Two popular such representations are the octal and the hexadecimal number systems. The former is based on grouping bits three at a time and is well suited to computers with 12, 18, or 36 bit word length; the latter, based on grouping bits by fours, is used for computers whose word lengths are multiples of four or eight. In Table I can be seen examples of these various number representations. Note that in the octal system there are no eights or nines; similarly in hexadecimal, the letters A through F are added to create a number system with 16 digits. Although these numeric representations seem awkward to those of us who are used to the decimal number system, they represent such an improvment over remembering sequences of zeroes and ones that computer programmers use them routinely for certain kinds of programming tasks.

TABLE 1: Number Representation for Sequences of Zeroes and Ones.

Decimal Number	Binary Number (3 groups of 3 bits)	Octal Number	Binary Number (2 groups of 4 bits)	Hexadecimal Number
0	000 000 000	000	0000 0000	00
1	000 000 001	001	0000 0001	01
2	000 000 010	002	0000 0010	02
3	000 000 011	003	0000 0011	03
4	000 000 100	004	0000 0100	04
5	000 000 101	005	0000 0101	05
6	000 000 110	006	0000 0110	06
7	000 000 111	007	0000 0111	07
8	000 001 000	010	0000 1000	08
9	000 001 001	011	0000 1001	09
10	000 001 010	012	0000 1010	0A
11	000 001 011	013	0000 1011	0B
12	000 001 100	014	0000 1100	0C
.				
.				
.				
24	000 011 000	030	0001 1000	18
.				
.				
.				
31	000 011 111	037	0001 1111	1F
.				
.				
.				
42	000 101 010	052	0010 1010	2A
.				
.				
.				
84	001 010 100	124	0101 0100	54

Generalized Scheme of Computer Architecture

It will now be advantageous to describe, in an admittedly simplistic manner, the building blocks which are common to all digital computers. In Figure 1 these components are depicted in a diagram which indicates the relationships between them. All computer components are divided into two general categories: the central processing unit which is often called the "mainframe" or the "CPU," and all other devices which are called peripheral units or simply "peripherals." The CPU consists of three sections: a control unit, an arithmetic unit, and the computer's main memory.

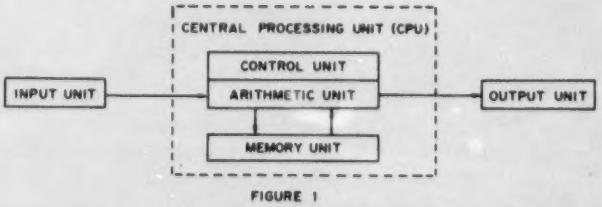

FIGURE 1

Fig. 1. Building blocks in a digital computer installation.

We can gain an appreciation of how computers operate by indicating the necessary sequence of events to accomplish a simple task such as the addition of two and five.

1. The instruction that addition is to be performed must be entered into the input device and transferred to the arithmetic unit.

2. The control unit must be advised that the sequence of zeroes and ones which now resides in the arithmetic unit should be interpreted as an instruction as opposed to primary data.
3. In preparation for addition, the arithmetic unit would now be reset to zero.
4. The first number, namely two, would be entered in the input device ad transferred to the arithmetic unit in the appropriate binary form.
5. The second number, five, would then be transferred from the input device. Since the arithmetic unit has not been reset to zero between steps 4 and 5, we now have in the arithmetic unit a sequence of zeroes and ones which represents the sum of the numbers we have entered.
6. In order for someone to know that this operation had in fact been carried out, it is necessary for the control unit to cause the value currently in the arithmetic unit to be transferred to the output unit preferably converted from binary representation back to the decimal number system.

In our simple example, the memory unit was not required. When more complicated procedures are to be carried out, the memory unit is used not only to store sequences of instructions called programs, but also to save any intermediate values required in the course of the calculations. It may be difficult to appreciate, but all computer programming ultimately must be reduced to simple incremental steps as illustrated in the example above.

Two Major Categories of Computer Utilization

As computers were developed, it was realized that these expensive devices required efficient utilization to justify their large initial cost. Two approaches to this problem emerged: the first, which permits the computer to schedule individual tasks one after the other, is called "batch-processing"; the second, which provides for a number of tasks to be accommodated by the computer apparently simultaneously, is called "time-sharing." Batch-processing is most suitable for such large tasks as payroll production, sending out bills, creating computerized files, or generating periodic reports. Time sharing, on the other hand, excels in those tasks which involve flexibility and minute to minute intervention by the human being undertaking the tasks; therefore it is used for inventory control, patient interviewing, citation retrieval, and computer assisted education. The largest computer facilities are able to undertake both batch-processing and time-sharing at the same time, but this is not true of all computers.

Levels of Interaction in Computer Systems

Just as the word hardware is used to refer to computer equipment, the term software is used to refer to the instructions to the equipment. This is somewhat of an oversimplification because there are at least three different levels of software with which to be concerned. As we try to understand how a computer functions we will take up each of these levels in turn.

Operating Systems—A digital computer, by itself, is a rather helpless device. It is entirely dependent on a set of instructions which permit it, or a human operator, to determine what task it is going to perform next. That portion of the total software is known as the "operating system" and varies widely in complexigy and capability with the size of the computer and the number of features available on the machine. In its simplest form, the operating system enables a user to load a program into the main memory unit of the computer and then tells the computer at what location in memory to begin execution. More sophisticated operating systems permit several programs to be processed simultaneously, which is called multiprogramming, and to keep track of many separate tasks even when they are being accomplished at vastly different speeds.

Computer Languages—As indicated earlier, the only language that a digital computer understands is binary, or "machine language" as it is sometimes called. One might legitimately ask why the machines were designed in this peculiar way. The answer is that the simplest, fastest, and most reliable device to be used as a computer component is a two position switch which is either on (on = 1) or off (off = 0). Once again the convenience, of the machine has been placed ahead of human convenience, but perhaps this is justifiable when one takes into consideration the strenuous requirements in terms of speed and reliability demanded of computer components.

The next step in intelligibility is what is known as "assembly language." Here the communication with the machine is done with a restricted set of abbreviations, called mnemonics, and symbols which are substituted for numerical representation of locations in the computer's memory. A program written in assembly language is called a "source program." Then the power of the computer is utilized to translate (the technical term is compile) the assembly language source program into a machine language version of that program. However, assembly language programming is really intended for computer professionals.

A third level of intelligibility is provided by languages such as FORTRAN, COBOL, BASIC, or FOCAL which are called high-level languages. The communication in these languages is even closer to natural English language, especially where the applications have a mathematical context. Some high-level languages such as FOCAL and APL are known as interpreter languages—the binary is created at each step in the program. Others, such as FORTRAN or COBOL, require that the entire program be compiled into a single machine language version at one time. Thus any small variation in the program necessitates compiling a new set of binary instructions. An interesting feature of BASIC is that it has both an interpreter and a compiler; thus programs written in BASIC are stored in source but executed in binary. Thus editing a program in source is readily available; when the correction is completed the program is recompiled for execution in binary. Where storing a program in its binary version is available, less room is required to store it on magnetic tape or disk than the source version.

One of the advantages of these generalized languages is that they are relatively the same from computer to computer, whereas each individual machine has its own binary and even assembly language instruction sets. Unfortunately, this advantage is more true in theory than in observance. There are many different versions of popular high-level languages such as FORTRAN and BASIC and often these versions are not exactly compatible from machine to machine.

Application Programs—In this final level of our discussion of software, we are dealing with the ultimate set of instructions which permit the computer to accomplish a specific task or application. If the purpose is to create a file of patient names which will store their office visits and treatment record, and can then be used to create monthly statements, that task can be done on a variety of computer equipment, with a variety of operating systems and in a variety of programming languages. In spite of this multiplicty of approaches, the final application program, which is what an office assistant would actually be working with, might be identical.

Another way of saying this is that good application programming attempts to minimize the restrictions imposed by the equipment, the operating system, or the computer language. Of course the size of CPU, the amount of available memory and the extent of bulk storage, have a great deal to do with the flexibility of the computer system. But with good design, the use of an interactive computer system need not be concerned with these matters. We say that the way in which the system accomplishes its work has been rendered transparent to the ultimate user. This, the theoretical goal of application programming, is never realized completely; however just as one need not understand how an automobile actually works to drive it, one can derive considerable utility from a computer terminal without having to understand how the system is accomplishing each specific task. The analogy is useful to make an additional point, one does have to learn how to drive an automobile. The knowledge required to do this is a small fraction of what must be known to repair it or to design a new one. So it is with interactive computing. A basic minimum of skill is needed to know how to make the connection to the computer system and how to interact with it successfully, but this a small fraction of what one needs to appreciate if one desires actually to write application programs. Similarly, writing application programs in a high-level language is a relatively simple task. Therefore many users will learn enough about the language they use frequently to make the minor modifications in their application programs which individualizes them for their own particular requirements.

The ability to refine continually a program until it does exactly what one desires it to do is the great virtue of the computer, particularly when it is used interactively. Then because our requirements do change with time, the ability to modify that program after it is considered perfect is also important. This is called software maintenance and is every bit as necessary as equipment, or hardware, maintenance. One should never purchase computer services without a clear understanding of who will be responsible for software maintenance and how it will be charged. Software that does not need to be altered exists only in the mind of the less-than-entirely-scrupulous, computer technology salesman.

Computer Versus Computer Terminal

The newcomer to computer technology sometimes is unclear of the distinction between computer and computer terminal. When computer meant a room full of large equipment, as is true for most batch-processing machines, and computer terminal meant the noisy teletype machine, the distinction was fairly obvious. Now with the advent of mini-computers and more complex terminals, the difference between a sophisticated terminal and a small computer is not so easy. In fact the term "intelligent terminal" has been coined to describe machines that have some stand-alone computing power but rely on a larger computer for assistance with bulk storage and the execution of larger programs. The important point to appreciate about terminals is that they generally rely on an ordinary telephone line for the connection to a computer. It is possible that most terminals will be acquired for communication with a single time-sharing computer, but this is not necessarily the case. A terminal is capable of communicating with a large variety of computers providing that the user has bona fide access to the remote computer.

At George Washington University Medical Center, our medical students communicate with the computers at Massachusetts General General Hospital, Ohio State University, the University of Illinois at the Medical Center, The State University of New York at Albany and the National Library of Medicine with the same terminals that they use to connect to our own educational time-sharing computer. It is not even necessary to pay long distance telephone charges for such use because of a Biomedical Communication Network maintained by the Lister Hill Center of the National Library of Medicine. Thus one should think of a computer terminal as a versatile device with potential access to the entire biomedical communication capability of the nation.

Reliability of Computational Devices

No discussion of computer fundamentals would be complete without bringing up the matter of reliability. If we are to substitute the computer terminal for an interacting human being, we have to have two types of assurance: first that the automated system will be at least as thorough as the human being, and second that the automated system will not become unavailable due to electronic failure just when we have become dependent on it. On the first point considerable data have already been accumulated. In the matter of acquiring patient information, an automated system is well accepted by a majority of patients and generally more thorough than the average physician. As to equipment failure, two approaches are possible. The manufacturer provides preferential maintenance service which guarantees repair effort on non-functioning equipment according to an established schedule. This is costly and does not prevent a failure at a crucial time, but it does assure that the equipment will be returned to complete functioning as soon as possible. The second approach is to design the computational facility with a certain amount of redundancy such that, if a key component fails, the processing load can be shifted to a duplicate. This capability is generally available in the larger commercial time-sharing services which have networks consisting of many separate computers to assure that customers will always have access to the service they require. Such reliability may necessitate storing key programs on more than one computer, but the extra storage charges are a small price to pay fo the assurance that equipment failure will not prevent utilization of this new resource when its is most needed.

Relation of Computer Technology to Medical Practice

If the reader has persevered and made some sense out of the preceding sections, he or she is now in a position to understand some of the difficulties which attend the application of this new technology to the practice of medicine. Lest any should doubt, the author is enthusiastic about the application of high-speed computational equipment for a broad variety of tasks in biology, medicine, and education. Nevertheless, so that false expectations are not raised, it is important to state in clear terms what can be done today, what is likely to be available soon, and what appears to be an unlikely development in the near future.

Today some very exciting programs are available in a variety of areas of interest to the physician. These include patient simulations for teaching special skills, computerized clinical consultant services, bibliographic citation retrieval, and even practical examinations for certification in some of the specialty boards. However, the surface is barely scratched as to what should be available to provide even a superficial coverage over the entire breadth of medicine.

In the near future we can expect increasing computerization of hospital records, increasing automatization of office visits and billing procedures, and increasing transmission of charts, X-rays, and so on over telephone lines. But, before you hurry out and ac-

quire a computer terminal, it would be wise to appreciate that today you will be in the vanguard of what is a nationwide research and development effort. If you enjoy doing it as a hobby, well and good; but it would seem unlikely, at the moment, that acquiring a computer terminal would save either much time or money. This is because there is not yet enough software directed at the physician's requirements.

Do not expect instant computer diagnosis for the entirety of medicine in the near future. Some people are working on this problem but it is very, very complex and involves a complete reorganization of the way in which computers work. Man in a split-second is able to recognize patterns. The neurophysiological techniques he used to do this are not yet understood, therefore it is not possible to incorporate them into computer technology. Until they are, the problem of computer diagnosis will remain an elusive goal.

How to Become Involved in Computer Technology

This is too broad a subject to cover in this short space but a few clues can be indicated. Most of the major medical center libraries have computer terminals. These were acquired to access a program called MEDLINE which is the National Library of Medicine's computerized citation retrieval service. At George Washington University Medical Center it is utilized daily by house officers who want up-to-date references on the patients they are treating. The major teaching hospitals have computer terminals and access to the Biomedical Communication Network referred to earlier. In Table 2 is a partial list of some of the program titles which can be retrieved.

Finally, you might consider adding a computer terminal to your office equipment but here a few words of warning are appropriate. More money will be spent on software development than hardware acquisition. Most computer systems take a year or more to become functional in a particular environment. Rely on a satisfied user for advice rather than a computer technology salesman; if the salesman cannot provide you with a satified user, be especially careful. Expect that your system will change with time; usually this means that you will increase your investment in hardware or software. The greatest value of computer systems is the relative ease with which they can be improved. But if you don't enjoy such a dynamic state, it may be better to wait until computer technology in support of medical practice is further advanced.

TABLE 2: Partial List of Programs Available from the Biomedical Communication Network

Massachusetts General Hospital
- Abdominal Pain
- Acute Joint Pain
- Anticoagulant Simulator
- Cardiac Arrythmias
- Cardiac Simulation
- Cardiopulmonary Resuscitation
- Coma
- Diabetic Ketoacidosis
- Digoxin Dosage Advisor
- Drugs in Renal Failure
- Hypertensive Emergencies
- Idiopathic RDS in the Newborn
- Jaundice

Ohio State University
- Acid-base Balance
- An Introduction to Computer Assisted Instruction
- Anticoagulant Medication
- Developmental Task Groups
- Juvenile Diabetes
- Medical Terminology
- Ophthalmoscopic Interpretation
- Psychotropic Medications
- Review Topics for Medical Personnel
- Septic Shock Care
- Short Topics for Patient Usage

University of Illinois at the Medical Center*
- Computer-Aided Simulation of the Clinical Encounter
- Computerized Random Item Bank

*Author's Note: As of 1979, the University of Illinois at the Medical Center is no longer on the Biomedical Communication Network, however the program entitled "Computer-Aided Simulation of the Clinical Encounter" is now available from Ohio State University.

THE ANALOG (COMPUTER) AS A PHYSIOLOGY ADJUNCT *(Part 1)*

Peter A. Stewart

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INTRODUCTION

The analog computer is a much maligned, sadly negected and yet a very helpful tool in physiology teaching and research laboratories. It should never have been called a *computer* - partly because what it does is so different from what digital computers do, and partly because then, perhaps, phyiologists and students who are "math-negatives" or "computer negatives," or both, would not be so likely to ignore it. In the hopes of minimizing emotional reactions, we shall refer to it as just an *analog,* an analog *computer,* from here on.

Historically, one of the classical analogs in physiology for many years has been the Wiggers' Model of the systemic circulation. While this analog took many local forms, they all had in common some sort of pulsatile pump, fed from a fluid reservoir of adjustable height, (the veins) pumping water through a valve into a low compliance large diameter tube (the arteries) from which the fluid flowed through an adjustable resistance (the arterioles and capillaries) back into the venous reservoir. Some of the hydraulic, and even physiologic, properties of the cardiovascular system can be demonstrated very well on this hydraulic analog, and properly used it can be very effective as a teaching device. This analog forms the conceptual basis for the cardiovascular model already described by Katz *et al* in their contribution to this series of papers.

Another very simple, qualitative analog for demonstrating the relationships between alveolar, pleural and external air pressures, thorax structures, and air flows in the respiratory system is often pictured in text books, and sometimes demonstrated in physiology lectures. It consists of a Bell jar representing the thorax, with two balloons inside, representing the lungs. The balloons are connected to the atmosphere via rigid tubes representing the bronchi and the trachea. A sheet of rubber, stretched acrosss the bottom of the Bell jar represents the diaphragm. Pulling down on the rubber sheet results in air entering the balloons; pushing up on the sheet causes air to leave. The analogy to normal quiet, diaphragmatic breathing is clear and direct.

Such physical models, while readily accepted as analogs, would probably not be designated as "computers" by the physiologists and their students who find them useful. The reason seems to be that they are *not* normally set up with measuring instruments to give quantitative data. Moreover they are usually not built with careful attention to quantitative matching between values of model variables (volumes, compliances, flow resistances), and values of the same quantities in the "real" physiological system. The tremendous advantage which the electrical analog has is that it is *so easy* to achieve that quantitative match merely by turning a few dials. No long hours in the machine shop, or searching for tubing with just the right elastic character *and* wall thickness *and* bore. All your hands have to do is twiddle knobs, flip switches, and plug in wires. The main work, as it should, involves the head! In order to know how to twiddle those knobs, you must have a very clear *quantitative* description of the system, because what you do when you "patch" - i.e. connect up - an analog, is create an electric circuit whose components are interconnected so as to obey *exactly the same quantitative relationships* as you claim are obeyed by the components of the physiological system you want to understand.

In the case of the mechanics of the respiratory system, for example, we could have capacitors representing compliances, electric resistors representing airflow resistances, voltages representing pressures, and currents representing air flows. Since we know the numerical values of all these entities in the normal real respiratory system, we can set our analog circuit values to those same numbers, and simply monitor its behavior with voltmeters and ammeters. Furthermore, since electrical plotting devices like oscilloscopes and pen recorders are rather common around a physiology department, we can hook them up to our analog and watch or record "behavior," just as we would do to ourselves or our experimental animals in a "wet lab" situation.

One may ask, on the other hand, if it's just the same as the person or animal, why use the analog? There are several answers and they appeal to different interests. First, with the analog it's very easy, and completely safe, to ask, and answer quantitatively, *any* meaningful question you wish to pose about how the real system would respond to any imagined changes in any desired variables. You can do any experiment you like on the analog; it can't hurt the analog, and , if the results indicate non-variable conditions, the experiment is immediately reversible just by re-setting the potentiometer knobs.

A closely related advantage is that you can measure any variable in the analog system without disturbing the system. You don't have to worry about the notorious reactivity and fragility of real living systems. No anesthetic deaths, for example. Even more interesting, many of those variables may be not accessible in the real system.

The inexorability and uncontrollability of *time* in real systems is also subject to easy modification in the analog. Time can be stopped, slowed down, speeded up, as you wish. The system behavior can be examined on different time scales, and this can be done repeatedly.

One more use for the analog is really in the realm of experiment, although it is more likely to be described as "mere" curve-fitting. If you know that the real system has a particular quantitative behavior, and there is one parameter in the system whose value you do not know - perhaps because it is inaccessible *in vivo* - then you can turn the knob which represents that parameter on the analog until the quantitative behavior of the analog accurately matches that of the real system. The knob setting then provides a reasonable estimate of the value which you would have measured for that inaccessible parameter if you could have!

Another psychological advantage to the analog is that it can never come up with long, completely meaningless, strings of

digits as if they were significant. It will tell you a pressure is 42 mmHg, not 42.032842936284 mmHg, for example. In general, its overall precision is about the same as real measurements on real systems, from 1 to 5%. It never tempts you to think you know a number to one part in a million billion just because your computer program uses double precision!

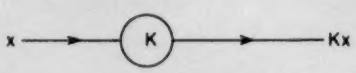
What about disadvantages? Criticisms of analog simulation mainly seem to be either criticisms of the foibles of the simulator (person), such as not including enough variables, for example, or invidious comparisons of the analog, as a device, with the digital computer, a very different device which can be programmed to *calculate* similar simulations. A good, fast, digital computer progra *can* produce the same results that an analog can in most situations, including run a plotter, but it does it differently; and it's *much* more difficult to understand how it is getting those results. What distinguishes an analog from a digital computer is that the analog is a physical (usually electrical) model of the biological system being analogized; it therefore simulates the physiological system by *behaving* like it, not by *calculating* the behavior as the digital computer does. The physical directness of the analog can make it much more meaningful and effective as a learning device than a set of equations, even though "in principle" they are the same.

One serious disadvantage of analog (computers) in comparison with digital computers is that analogs are more often "hardware limited." This means that if you want to analyze a bigger system, you need more components - amplifiers, pots, etc. In a digital computer simulation, you simply have to write a longer, possibly more complicated, program, but it will usually still run on the same machine; it will just take longer. This limitation on analogs is a real one, especially in research applications, but is seldom incapacitating in a teaching-learning situation. If you run out of hardware, chances are your model is too complicated to be a useful learning device. Sucessful analogizing involves abstracting and simplifying, and these are also essential components of successful teaching.

WHAT IS AN ANALOG (COMPUTER)?

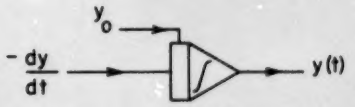
In current use, an analog computer is a conveniently arranged set of electronic circuits, plus a "patch panel" which enables the operator to interconnect them, so that the quantitative relationships between them are just the same as those specified for the "real" system being analyzed. At the simplest useful level, the basic circuits provided are generally the following:

1. *Potentiometer.*
(universally designated "pot".) This is a simple rotary voltage divider, usually requiring 10 or 15 turns to go from zero to full output, with a remarkably accurate mechanical scale attached to the knob. A pot produces an output voltage K times the input voltage, where K is the fraction of its total travel its knob is set to, and is therefore not greater than 1.0. The symbol for a pot is:



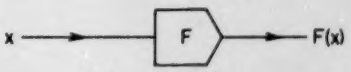
2. *Operation amplifiers.* (known as "op amps" or just "amps".) An op amp is a high gain DC amplifier connected, usually on the patch panel, into a feedback circuit which results in the desirable properties of very low output impedance, high input impedance, and overall circuit gain determined only by the ratio of feedback to input resistors. Op amps usually produce an output of opposite sign to the input, so they are also called "inverters" or "sign changers". An op amp will accept more than one input, and produce an output equal to (minus) their algebraic sum, so it can also be called a "summer" or "adder"
The symbol used for a connected op amp is:

3. *Integrator.* This is an op amp with a capacitor instead of a resistor in the feedback circuit. Its output voltage is the negative time integral of the input voltage. It must also be supplied with an "initial condition", the value of the output when time = 0. Its symbol in analog diagrams is:



4. *Multipliers* (dividers). These circuits take advantage of the algebraic fact that $(a+b)^2 = a^2+2ab+b^2$ and $(a-b)^2 = a^2-2ab+b^2$ so that $(a+b)^2-(a-b)^2 = 4ab$, as well as the electronic fact that it is not difficult to make a circuit which produces the square of its input. By changing the input and output connections, the same circuit can also be made into a divider. Usual symbols are:

5. *Function generators.* These are surprisingly simple circuit boxes, with large numbers of screwdriver controls, which permit adjustment of both the magnitude and slope of the output voltage as a function of input voltage. They can be set up to approximate very well a large variety of empirical curves. (for example, the hemoglobin-O_2 dissociation curve.) They are usually symbolized by:



To use these five types of circuits, you connect them together by plugging in wires on the patchboard in such a way that the operations they will carry out match precisely the operations indicated by the equations which describe the system you wish to study.

How each of these "black boxes" does what it does is not difficult to understand at the level of the usual freshman physics course, and is generally well explained in books on analog computing, or handbooks provided by manufacturers. What matters most is that such devices do exist, and carry out, remarkably reliably, the indicated operations.

Before wiring a real problem on a patchboard, it is always helpful, and usually essential, to re-write the equations for the problem in the language of the above circuit symbols, thereby converting the equations into an "analog diagram". Such a diagram is not only a guide to the actual wiring of the patchboard, it is also a very informative way of displaying many aspects of the information content of the equations, as well as the properties of the system.

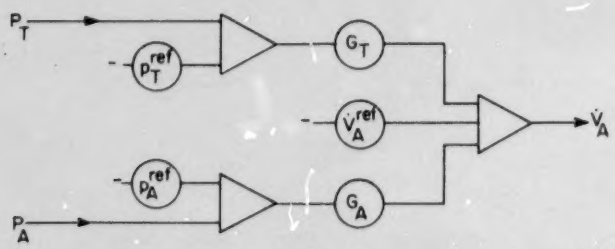
A SIMPLE (ALGEBRAIC) EXAMPLE: THE RESPIRATORY CONTROL FUNCTION

Chemical control of alveolar ventilation has been a favorite topic for mathematical modelling, and we shall discuss a simple model for the whole system in the next section. It most such models, for conditions not too far from physiologically normal values, the basic control can be satisfactorily represented by a linear controller with different sensitivities to CO_2 partial pressures in body tissues (or venous blood) and in alveolar gas (or arterial blood). The simplest equation to represent such a control function is:

$$\dot{V}_A = G_T \cdot (P_T - P_T^{ref}) + G_A \cdot (P_A - P_A^{ref}) + \dot{V}_A^{ref} \qquad (1)$$

Where G_T and G_A are "gains" or "sensitivities", P_T^{ref}, P_A^{ref}, and $\dot{V}_A^{ref}$ are "set points" or reference values, $\dot{V}_A$ = aleolar minute ventilation, P = CO_2 partial pressure, "T" means "tissues" and "A" means "alveoli."

If voltages representing P_T and P_A can be assumed to be available, then the analog representation of this equation is simply:



The five parameters in equation (1) are represented by 5 pots, which must be set to appropriate values in order to achieve the desired match with experimental behavior. Reasonable values for the author turn out to be:

$$\dot{V}_A = 2.0\,(P_T - 46) + 0.20\,(P_A - 40) + 7.0 \qquad (2)$$

Going from this equation and the above diagram to actually connecting up (patching) the analog requires one more step, because the analog can only deal with voltages up to a fixed limit, 10 volts or 100 volts, depending on the manufacturer. Equation (2) must therefore be re-written with new ("scaled") variables, proportional to the real ones, so that all numerical values are within acceptable limits. Finding suitable conversions, or scaling factors, is easily done systematically by defining analog variables as follows:

$$p\ (\text{volts}) = K_p \times P\ (\text{mmHg})$$
$$\dot{v}_A\ (\text{volts}) = K_V \times \dot{V}_A (\text{Liters/Min})$$

Equation (2) then becomes:

$$\frac{\dot{v}_A}{K_V} = 2.0\,(\frac{p_T}{K_p} - 46) + 0.20\,(\frac{p_A}{K_p} - 40) + 7.0$$

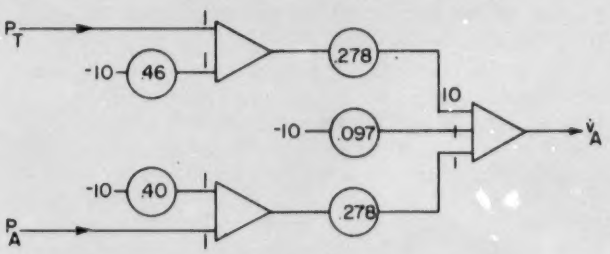
or

$$\dot{v}_A = \frac{K_V}{K_p} \times 2.0 \times (P_T - 46) + \frac{K_V}{K_p} \times 0.20 \times (P_A - 40) + 7.0 \times K_V \qquad (3)$$

Choosing $K_V = 0.139$, $K_p = 0.1$, this becomes:

$$\dot{v}_A = 2.78\,(P_T - 4.6) + 0.278\,(P_A - 4.0) + 0.97 \qquad (4)$$

The coefficients larger than 1.0 are taken care of by amplifying the pot outputs by 10 rather than 1, which is easily done by patching an op amp input with an input resistor 1/10th as large. The final scaled analog diagram now looks like this:



This analog circuit will produce a voltage, v_A, proportional to V_A, which is determined by P_T and P_A in exactly the way that equation (2) says V_A is determined by P_T and P_A. If P_T or P_A increases, v_A will increase, and vice versa. If P_T = 4.6, and p_A = 4.0, than P_A = 0.97, corresponding to the physiological values of V_A = 7.0L/Min when P_T = 46 mHg and P_A = 40 mHg. in this subject.

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SECTION THREE - USE OF COMPUTERS IN THE PHYSIOLOGY LABORATORY

Chapter Six

TEACHING COMPUTER LITERACY AND PHYSIOLOGICAL SIMULATION

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RATIONALE FOR SUCH INSTRUCTION

Without doubt, the modern digital computer is playing an ever-increasing role in many facets of human endeavor. At The George Washington University Medical Center we believe that each medical student should be exposed to computer technology for several reasons. First, there is currently available a relatively large data-base of computer assisted educational materials which can substantially improve learning in the health sciences (4). Second, many of the computer-based learning experiences are simulations of clinical situations in which the student is given opportunities to "learn-by-doing" that would not be practical with real patients. Third, and perhaps most important, these computer terminal based encounters are similar to the interactions between the physician and the computer which are likely to play an increasingly important role in the future practice of medicine. In the past, a few great physicians with encyclopedic minds have been able to practice at very high standard of medicine. In the future, this improved capacity for relating the present situation to earlier experience will be extended to all physicians who are willing to learn how to make use of computer stored information.

The skills involved in communicating with a computer by way of a computer terminal are not extensive. One can learn the rudiments in less than an hour. But, like the more complex skills utilized in physical diagnosis, one must use them regularly in order to be successful in extracting the maximum amount of information in the minimum amount of time. It can be argued that technicians will be deployed to undertake such information retrieval; but, in my opinion, the physician who is not convinced personally of the utility of an approach is unlikely to foster its development in ways which will assure the value of the technology to the profession. Fortunately for the medical student, those skills acquired now immediately provide a powerful adjunct to the learning process, and eventually they can pave the way for access to the enlightened practice of the future. It is in support of this aspiration that every medical student is given an exposure to computer-based learning and/or physiological simulation as part of the laboratory work in the required freshman medical physiology course. The present effort has evolved from a program described several years ago (5).

RESOURCES UTILIZED FOR SUCH INSTRUCTION

The resources available for this enterprise can be subdivided into hardware, software, people and time. A similar learning experience could be mounted with fewer resources; those identified below represent the ones available to our particular effort.

Hardware. We make use of the facilities sponsored by the Health Education Network, Inc. to engage the health educational programs of Masschusetts General Hospital (MGH) and The Ohio State University (OSU). The physical connections are made over the hardware network operated by TMYSHARE, Inc., an international computer network with access by local telephone service in over 60 of the larger cities in North America. Additionally, through the courtesy of the Division of Computer Research and Technology of the National Institutes of Health (NIH) we are able, again with a local telephone call, to utilize three physiological simulation programs originally developed at McMaster University in Hamilton, Canada. Finally, we also make use internally of two medium sized mini-computers: a Digital Equipment Corporation (DEC) PDP-12 and a DEC PDP-8/E.

Student ability to engage in interactive computing occurs in the Audio Visual Education Center of the Paul Himmelfarb Health Sciences Library where there are two Tektronix 4010 Storage Tube Computer Terminals and a Tektronix 4600 Hard Copy Unit. Connections are made by way of Bell System Data telephones so that these same terminals can be interfaced with any of the several computers identified in the previous paragraph. Additional terminals are also available in the Office of Computer Assisted Education and Services where the two mini-computers are located.

Software. In Table 1 can be found a partial list of the programs used and their source. The intent of these instructional sessions is to expose medical students to programs they have not previously seen, therefore the list of programs actually used is considerably longer. It can be seen that through the use of networking, multilingual access beyond the capabilities of any single computer is made possible. An additional software resource available at MGH and OSU is utilized consisting of a reservation capability which guarantees access to an entry port for a particular day and time, on a previously agreed basis.

TABLE 1

Name of Program	Program Type	Computer Language	Source
TERMLEARN	Tutorial	FOCAL	GWUMC
ROCKET	Simulation*	FOCAL	GWUMC
Acid Base CHEMistry	Tutorial*	FOCAL	GWUMC
CELLMBrane	Simulation	BASIC	GWUMC
MACMAN**	Simulation	FORTRAN	NIH
MACPUF	Simulation	FORTRAN	NIH
MACPEE	Simulation	FORTRAN	NIH
Cardio Pulmonary Resuscitation	Simulation	MUMPS	MGH
Diabetic KetoAcidosis	Simulation	MUMPS	MGH
ACId BAse chemistry	Tutorial	Coursewriter	OSU
Computer-Aided Simulation of the clinical Encounter	Simulation	Coursewriter	OSU

*Programs indicated thus make use of computer-driven graphics and require a Tektronix 4010 or equivalent terminal.

**An earlier version of this program is also available from MGH under the name Cardiac SiMulation.

People. The freshman medical school class consists of 150 persons who are divided into nine groups for laboratory work. In order to assure a satisfactory experience for persons without previous exposure to interactive computing, a student to instructor ratio of no greater than 6 to 1 is desirable. Accordingly, three instructors and three computer terminal stations are available for each laboratory group of 15-17 students. It has been found that working in groups of up to six students at a single terminal is highly satisfactory. In fact, the student interaction which takes place before a response is made to the program, represents one of the most effective teaching portions of the entire experience.

Time. A complete afternoon is set aside for these laboratories. For the most part, the sessions begin to wind down in two to three hours; but, occasionally, an enthusiastic group will keep involved for longer periods. The amount of material appropriate for freshman medical students available in this mode of instruction approximates several hundred hours of terminal interaction, therefore it is only possible to open a doorway into this new world with a single short session.

A multiplication effect can be achieved by demonstrating different programs to different groups. In this way as they discuss the experience with their classmates, the students realize that the data-base is actually larger than the items which they have seen.

FORMAT OF THE SESSIONS

The laboratory session begins in a conference room. A handout is provided which lists the intended objectives, the computer systems available, and makes recommendations as to programs available as well as giving details on how to call up the specific programs (see Appendix). Some preliminary discussion on computer technology is developed. The instructor queries each student about previous exposure to computer technology, in general, and computer-based instruction, in particular. (In most groups, persons without any previous computer experience predominate.) The distinction between "batch-processing" and "interactive computing" is presented. Current capabilities for computer-based learning in the health sciences are introduced and potential uses for such techniques in the practice of medicine are developed. Group participation is encouraged and expectations with regard to computer diagnosis or fears about computers replacing physicians are placed in the context of the current capabilities and limitations of the technology. When the discussion begins to slow down, the group is divided into three sections, the instructors are assigned, and the practical work begins after moving to the area where the computer terminals are located.

For students without previous exposure to interactive computing, the program TERMLEARN which was developed by this Office and runs on the DEC PDP-8/E, is the initial and pivotal learning experience. As the name implies, this program is intended to teach the student the rudiments of interacting with a remote computer by using a computer terminal. Our student terminals (Tektronix 4010) consist of view screen and an integrated typewriter-like keyboard which can be connected to a computer by way of a conventional Bell System Data-phone using an ordinary, voice grade, telephone line. The computer can display letters or numbers as well as line drawings, charts or graphs on the view screen and the student types responses as the program proceeds; the latter are also displayed on the view screen before being sent to the computer for interpretation. A typical dialogue is shown in Figure 1. TERMLEARN is able to simulate the manner in which other computers require the student to communicate with them. Each computer is idiosyncratic in these communication details which are summarized in TERMLEARN where they can be practiced on our internal equipment prior to attempting a sign-on to a more remote system.

After some familiarity with the terminal has been achieved, we utilize a computer program called ROCKET to introduce the students to the concept of simulation. This program is a simulation of a lunar landing. The rocket starts at 500 feet from the lunar surface and is traveling at 50 feet/second. Retro rockets can be fired to slow the rate of descent but the amount of fuel is limited and must be used judiciously. The objective is to make a soft-landing of the rocket which is defined as landing with a velocity of 7 feet/second or less. A sample run is shown in Figure 2.

IN ORDER TO GIVE YOU PRACTICE CORRECTING ERRORS, TYPE THE WORD STOP AFTER THE COLON BELOW AND CORRECT IT TO THE WORD GO BEFORE SENDING IT TO THE COMPUTER.

: STOP < CR >*

NO! YOU HAVE SENT THE WORD STOP TO THE COMPUTER. TRY AGAIN.

: STOP < CR >

NO! DID YOU FORGET TO TYPE GO ? PLEASE TRY AGAIN.

: STOPGO < CR >

NO! THE SHIFT KEY WAS NOT DEPRESSED WHEN YOU TYPED 0 . TRY AGAIN.

YOU SEEM TO BE HAVING DIFFICULTY. IF YOU NEED SOME HELP, REQUEST ASSISTANCE FROM SOMEONE FAMILIAR WITH USING A COMPUTER TERMINAL; OTHERWISE, TRY AGAIN.

: STOP_GO < CR >

VERY GOOD!

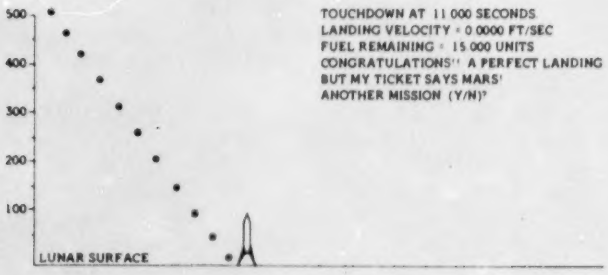
PRESS THE RETURN KEY WHEN YOU ARE READY TO CONTINUE.

*Note: User's entries are underlined for purposes of illustration.

Fig. 1 A sample dialogue taken from the section on Correcting Errors in the computer program TERMLEARN. The portions which are underlined are those typed by the student. The symbol <CR> signifies that the carriage return key has been pressed to send the message to the computer. The symbol – indicates that the special character key which deletes all input back to the colon (:) has been pressed. Note that the computer has been programmed to interpret different incorrect responses and to vary the feedback appropriately; after three errors a special message is displayed encouraging the student to be more careful or to get assistance.

It might seem as if this exercise is trivial and more in the nature of entertainment than instruction. However, it has been included in the laboratory after discovering that to teach to computer naive students the concept of simulation with biological content imposes a triple burden: learning about computers, understanding simulation technique and mastering biological material. Until we introduced the ROCKET program, many students experienced difficulty with the transition from TERMLEARN to either the CELLMBrane simulation or the more complex MACMAN simulation. Now, without spending very much time on ROCKET, the students move to the other programs with greater ease and confidence.

```
SEC    FEET   SPEED  FUEL   BURN
 0     500     50    120    ?5  < CR >
 1     450     50    115    ?5  < CR >
 2     400     50    110    ?5  < CR >
 3     350     50    105    ?5  < CR >
 4     300     50    100    ?5  < CR >
 5     250     50     95    ?5  < CR >
 6     200     50     90    ?5  < CR >
 7     150     50     85    ?5  < CR >
 8     100     50     80    ?5  < CR >
 9      50     50     75    ?30 < CR >
10      13     25     45    ?30 < CR >
```




```
SEC    FEET   SPEED  FUEL   BURN

TOUCHDOWN AT 11 000 SECONDS
LANDING VELOCITY = 0 0000 FT/SEC
FUEL REMAINING = 15 000 UNITS
CONGRATULATIONS!! A PERFECT LANDING
BUT MY TICKET SAYS MARS!
ANOTHER MISSION (Y/N)?
```

Fig. 2 **A sample run for the computer simulation program ROCKET. Note that the position of the rocket after each decision was calculated and plotted on the graph with an asterisk. Only when a perfect landing is made does the picture of the rocket get created by the program. Such pictorial capabilities require a special terminal such as the Tektronix 4010.**

DESCRIPTIONS OF SIMULATION PROGRAMS

CELLMBrane. This program is a simulation of a single cell wherein the student is responsible for maintaining, for a specified number of cycles, the cell's contents of water, sugar, waste, sodium, potassium and chloride within limits that are compatible with keeping the cell alive. A sample run indicating the initial conditions and the limits for a cell of medium difficulty is shown in Figure 3. Only one of the above quantities can be altered per cycle, and there are obligate changes in each of the quantities which take place automatically for each cycle. A warning message is given to the student when a quantity exceeds its safe limit. A crisis message is given to the student when a quantity will exceed its death limit on the next cycle. Cells may die either by having any quantity exceed its death limit or by accumulating too many consecutive warning and/or crisis messages. Cells of differing degree of difficulty are available and there is an option which permits the instructor or the student to create new cells. One of the major utilities of this simulation program is that it causes the student to appreciate that many processes are going on at different rates but simultaneously, in order for cells to survive.

MACMAN, MACPUF, and MACPEE. The three simulation programs developed at McMaster University differ in content, complexity and time frame; but they utilize a similar format hence they will be discussed together.

MACMAN, the first of the programs to be developed, has recently undergone a major revision which has introduced some simplification and improved program flow. It consists of a computer simulation of the heart, peripheral circulation, and arterial baroreceptor functions. The variables displayed graphically include pulse rate, diastolic blood pressure and systolic blood pressure as a function of time. The following additional data items are printed after the graph: mean arterial blood pressure, right atrial blood presure, mean capillary blood pressure, cardiac output, stroke volume, arterial resistance, venous resistance, and cardiac contractility. The five variables which can be varied in-

```
*** CELL MEMBRANE ***

INSTRUCTIONS (0 = YES, 1 = NO)? 0 < CR >

YOUR MISSION: SHOULD YOU CHOOSE TO ACCEPT IT, WILL BE TO CONTROL
A CELL MEMBRANE AND TO ATTEMPT TO KEEP A CELL ALIVE UNTIL IT
REACHES MATURITY. EACH INTERACTION YOU HAVE IS A CYCLE IN
THE CELLS LIFE. IN ADDITION TO THE CHANGES YOU SPECIFY IN EACH
CYCLE, THE CELL IS USING ENERGY AND PRODUCING WASTE, ETC.
THUS THE CONDITIONS OF THE CELL ARE CONSTANTLY CHANGING, AND
YOU MUST MANAGE THEM IN ORDER TO KEEP THE CELL ALIVE.

CHOOSE THE CELL YOU WOULD LIKE TO MANAGE
1 - AN EASY CELL
2 - A MEDIUM DIFFICULTY CELL
3 - A DIFFICULT CELL
? 2 < CR >

THE FOLLOWING TABLES WILL DELINEATE THE PHYSIOLOGY OF YOUR
CELL. YOU SHOULD KEEP THESE TABLES HANDY AS YOU ATTEMPT TO
MAINTAIN THE CELL.

                 THE LOWER   THE LOWER   INITIAL          THE UPPER   THE UPPER
* PARAMETER      DEATH LIMIT SAFE LIMIT  SETTING  +OR-  SAFE LIMIT  DEATH LIMIT
1 WATER          3000        6000        7000     500   8000        11000
2 SUGAR          4           8           30       5     45          70
3 WASTE          0           0           3        3     15          25
4 SODIUM         0           0           2        2     13          23
5 POTASSIUM      30          40          53       0     53          54
6 CHLORIDE       0           0           1        0     1           3

YOUR CELL WILL TAKE 9 CYCLES TO REACH MATURITY
THE CELL WILL DIE IF ANY PARAMETER EXCEEDS ITS DEATH LIMITS
OR IF 6 CONSECUTIVE WARNINGS OR CRISES ARE GIVEN. A
WARNING IS GIVEN IF A PARAMETER EXCEEDS ITS SAFE LIMITS.
A CRISIS OCCURS WHEN A PARAMETER WILL EXCEED ITS DEATH
LIMITS DUE TO ITS OBLIGATORY CELLULAR CHANGES ON THE CURRENT
CYCLE UNLESS AN INTERVENTION IS MADE. FOR ANY INTERVENTION
1 WASTE MOLECULE IS PRODUCED FOR EACH 6 SUGARS USED.

PRESS THE CARRIAGE RETURN KEY WHEN YOU ARE READY TO CONTINUE? < CR >


CYCLE 1 - THE PRESENT CONDITIONS ARE AS FOLLOWS:
  1 WATER MOLECULES 7113          4 SODIUM IONS 3
  2 SUGAR MOLECULES 27            5 POTASSIUM IONS 50
  3 WASTE MOLECULES 0             6 CHLORIDE IONS 1

ENTER: 0 FOR OPTIONS AND LIMITS, ITEM NUMBER TO CHANGE, OR
9 FOR CALCULATOR MODE? 1 < CR >
HOW MANY WATER MOLECULES WOULD YOU LIKE TO GET RID OF?
```

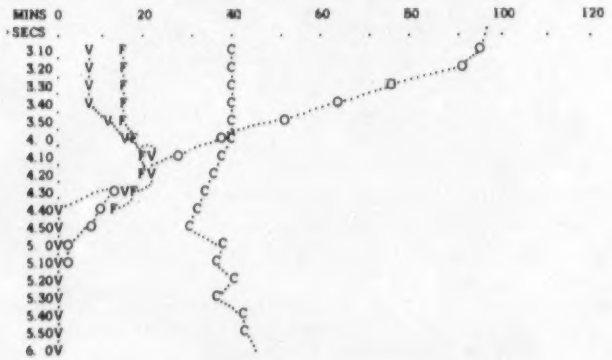
Fig. 3 **A sample run for the computer simulation program CELLMBrane. Note that the instructions include tables specifying the safe and death limits for the particular cell being simulated at that time.**

dependently by the student are: 1) arterial resistance, 2) venous resistance, 3) cardiac contractility, 4) mean intrathoracic pressure, and 5) blood volume. It is also possible to alter baroreceptor function. After running the simulation for fifteen 4 second intervals, the computer stops and gives the student an opportunity to: 1) *change* any of the independent variables or the baroreceptor status, 2) continue the simulation for another minute, 3) *restart* which discontinues the current simulation and sets up a new patient and 4) *stop* which takes the student out of the program and into a level of the system where a different program can be engaged or a legal disconnect from the system can be made. This same control query is used in MACPUF and MACPEE as well. A 28 page manual on MACMAN is available from McMaster University. The latter includes suggestions for 16 experiments which can be performed on this simulated patient. Some comments by the patient are made occasionally during the simulation especially if certain variables reach extreme values.

MACPUF is a computer simulation of gas exchange and circulation; it is more complex than MACMAN but still only at a moderate level of complexity. The graph plots minute ventilation (V), respiratory rate (F), arterial partial pressure of carbon dioxide (C), and arterial partial pressure of oxygen (O) against time. A sample run after the level of inspired oxygen has been changed from 20.93 to 0.0 vol % is reproduced as Figure 4. Note that an additional option to *inspect* has been added to the capabilites

available to the student. The latter produces more data than the abbreviated version which follows each new graph. Here too, a detailed manual on the program is available from McMaster University. It consists of 38 pages and includes 6 "physiological" experiments as well as 15 "clinical" experiments which can be performed on the model. A separate 3 page Commentary on the MACPUF experiments and problems for tutors is also available.

```
DO YOU WANT TO.  1. CHANGE, 2. CONTINUE, 3. RESTART, 4. INSPECT, 5. STOP
? 0 < CR >

1 IS OBVIOUS, 2 STARTS ANOTHER RUN OF STANDARD 3 MIN
3 STARTS AGAIN WITH A NEW SUBJECT, 4 PRINTS A TABLE OF MOST
USEFUL VALUES, 5 STOPS THE PROGRAMME
PLEASE TRY AGAIN
? 1 < CR >

1. CHANGE VALUES, 2. NAT/ART VENT, 3. STORE/BKTRK, 4. RUN CHANGE, 5. PRESETS
? 1 < CR >

TYPE NUMBER OF FACTORS (1-99) TO CHANGE, OR 100 FOR SPECIAL EXPTS
? 1 < CR >

FACTOR 1 (CURRENT VALUE= 20.9), SPECIFY NEW VALUE
? 0 < CR >

DO YOU WANT TO.  1. CHANGE, 2. CONTINUE, 3. RESTART, 4. INSPECT, 5. STOP
? 2 < CR >
```




```
FINAL VALUES FOR THIS RUN WERE...

ARTERIAL PO2 =     9, O2 CONT =     .1, O2 S          0.
ARTERIAL PCO2= 40.2, CO2 CONT=  47.7
ARTERIAL PH  =  7.38( 42.NM), ART.BICARBONATE= 22.0

RESPIRATORY RATE =  .0,  TIDAL VOL. =  10. ML
TOTAL VENTILATION=  .0 L/MIN, ACTUAL CARD. OUTPUT=   5.5 L/MIN
TOTAL DEAD SPACE= 63.8 ML, ACTUAL VENOUS ADMIXTURE=  4.4 PERCENT

1. INSP. O2=   1., 2. CO2=  0. PERCENT,  3. NOM. CARD. OUTP.=  5.0 L/MIN
4. TISS. METAB.= 100.,  5. VENOUS ADMXT.= 0s,  6.D.SPACE+=      0. ML

YOUR PATIENT IS UNROUSABLE

YOUR PATIENT IS VERY BLUE

DO YOU WANT TO.  1. CHANGE, 2. CONTINUE, 3. RESTART, 4. INSPECT, 5. STOP
?1  CR >
```

Fig. 4 Sample run from the computer simulation program MACPUF. Note a) the alteration of the inspired oxygen from 20.93 to 0.0 vol. %, b) the resultant fall in arterial partial pressure of oxygen to low values in two minutes, and c) the nursing notes indicating the dire state of the simulated patient.

MACPEE is a computer simulation of the heart, peripheral circulation, kidneys and body fluid compartments. It includes most of the MACMAN capabilities but operates on a slower time frame so that each cycle consists of six four hour periods making up a full 24 hour day. The graph depicts only the diastolic and systolic blood pressures and the heart rate but the accompanying table includes complete fluid balance and electrolyte information. Three of the five independent variables from MACMAN are available for change: rterial resistance, venous resistance and cardiac contractility. To these has been added sodium intake and renal sodium reabsorptive rate, protein intake and urinary protein loss, potassium therapy which may add potassium or remove it, glomerualr filtration rate, as well as the levels of aldosterone and anti-diuretic hormones. In actuality any of MACPEE's 96 variables can be altered by use of the *change* command which makes this program more sophisticated than its predecessors. The 34 page manual which includes 10 MACPEE problems is currently undergoing revision at McMaster University.

Cardiopulmonary Resuscitation (CPR) and Diabetic Ketoacidosis (DKA). These two simulations originally developed at Massachusetts General Hospital are less physiological models than behavioral simulations. CPR uses questions followed by multiple choice answers to guide the student through a cardiac arrest situation. By means of skillful use of random selection at multiple re-entry points, the program creates a veritable infinity of clinical situations which are different each time the student requests the program. Three sample interactions are shown in Figure 5. The authors of the program have provided a detailed description (2).

```
                                        Cardiopulmonary Resuscitation

Three different segments of student's interaction with Cardio Pulmonary
Resuscitation Program

THE PATIENT IS AN 81 YEAR OLD MAN WHO IS 2 DAYS POST CATARACT EXTRACTION
YOU ARE A STAT CONSULT BECAUSE THE PATIENT DOES NOT LOOK RIGHT.
   WHAT DO YOU DO FIRST?

1. TAKE AN EKG
2. START AN IV
3. CHECK MAJOR VESSELS FOR PULSES, SEE IF PATIENT IS RESPONSIVE.
4. GIVE A SHOT OF INTRACARDIAC EPINEPHRINE

> 1 < CR >

   THAT WILL TAKE SEVERAL MINUTES ASSUMING YOU HAVE AN EKG
MACHINE IN THE ROOM AND LONGER IF YOU HAVE TO GET ONE.....
THE PATIENT, IF TRULY ARRESTED, WILL BE BEYOND
RESUSCITATION BY THE TIME YOU DOCUMENT THE FACT.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   THE BICARB IS RUNNING. NOW IT IS TIME TO TRY SOME SPECIFICS.
LET'S TAKE A LOOK AT THE PATIENT'S RHYTHM.

THE RHYTHM STRIP IS SHOWN ON PAGE 6, IS THIS

1. VENTRICULAR FIBRILLATION
2. VENTRICULAR TACHYCARDIA
3. SLOW IDIOVENTRICULAR RHYTHM
4. ELECTROMECHANICAL DISSOCIATION

> 2 < CR >

   CORRECT. NOTE THAT IT COULD ALSO BE THE SINE WAVE OF
HYPERKALEMIA, A CHOICE YOU WERE NOT OFFERED.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   THE FIRST SHOCK TOOK YOU FROM V TACH TO VF SO AN
IMMEDIATE RESHOCK IS REASONABLE, IN FACT...

   A FEW SECONDS OF ASYSTOLE...
THEN GOES TO THE RHYTHM SHOWN ON PAGE 3.

WHAT WOULD YOU LIKE TO DO...

1. DEFIBRILLATE AGAIN
2. GIVE 1 MG EPINEPHRINE IV, MASSAGE, THEN SHOCK
3. START A LIDOCAINE DRIP THEN SHOCK

> 3 < CR >

   THAT MAY WORK, THOUGH IN THE SETTING OF FINE FIBRILLATION MY FIRST
CHOICE WOULD HAVE BEEN EPI. THE XYLOCAINE IS RUNNING AT 4 MG/MIN, SHOCK, AND...
```

Fig. 5 Three sample fragments from the computer simulation program Cardio-Pulmonary Resuscitation. The upper sequence is the initial frame; the second sequence takes place after the patient has been stabilized and an electrocardiogram is available; the third sequence indicates the handling of therapy options. Note the constructive use of creative feedback in all three instances.

DKA is even more clinically oriented but with a little assistance freshman medical students are able to manage because the program is primarily concerned with only three variables: insulin therapy, fluid replacement, and potassium blood level. The initial vignette is followed by opportunities to obtain details of the physical examination, results of laboratory studies, and the ability to write clinical orders for the next therapy period of one hour. The free-text entry provides a new level of sophistication and realism. This program also is documented in the literature (3).

Computer Aided Simulation of the Clinical Encounter (CASE). This program was originally developed at the University of Illinois College of Medicine but is now available from The Ohio State University. Unlike the sophisticated offerings of MGH which create a new and different patient each time the student engages the program, CASE's patients are fixed; once the selection of a particular patient is made, however there are many different patients programmed, 24 as of this writing and the file is being added to on a regular basis. Because the patients are specific, they are able to cover a broad range in the field of medicine and several different clinical specialties are represented. All queries are made by the student in his/her own words and the computer interpreter is reasonably versatile at determining what the student has in mind. The sections of the programs deal with history, physical examination, laboratory, and active management which includes diagnosis and treatment. The program has been described in detail by its originators (1).

It is probable that this program is beyond the capabilities of a freshman medical student since it expects the user to be familiar with the details of a medical work-up and calls on additional information from a diagnostic and therapeutic point of view. It has frequently been used in our demonstrations for a number of reasons: a) to show a well-designed clinical simulation with considerable flexibility, b) to satisfy the unrequited urge for exposure to clinical situations which is common to most first year medical students, and c) to suggest that there are computer-driven learning experiences available for later stages of the curriculum. This particular program also has an analysis section which provides feedback on the areas of inquiry or examination which should have been elicited to arrive at the correct diagnosis. The latter is useful to suggest that clinical problem solving can be approached on a rational basis.

SUMMARY AND CONCLUSIONS

The average medical student, even those who come from undergraduate institutions with active computer science programs, is inexperienced in the use of computer-based learning programs. A relatively large data-base of computer assisted educational materials exists for the health sciences. A nationwide network dedicated to low-cost access to these teaching programs facilitates their distribution. Medical students using these instructional dialogues with a computer are able to obtain personal involvement in medical management without risk to human patients and at early stages in their training which stimulates motivation to learn. Programs in physiological simulation can be an adjunct to the appreciation of homeostasis and the complex and simultaneous inter-relationships among various physiological systems. Laboratory sessions which deal with computer-based learning are well-received by freshman medical students. A ratio of 4-6 students per instructor at each computer terminal is feasible. It is desirable to have access to more than one computer system to assure that the demonstration is not flawed by technical difficulties. Interactive computing promises to play an increasing role in the enlightened medical practice of the future, thus early involvement of the would-be practitioner with this versatile technology seems especially desirable.

APPENDIX

GEORGE WASHINGTON UNIVERSITY MEDICAL CENTER OFFICE OF COMPUTER ASSISTED EDUCATION AND SERVICES

Objectives of Computer Simulation Laboratories

1. To provide an exposure to computer-based learning experiences for those who have not accessed them before.
2. To provide an indication of the variety of programs that are available to the GWU medical student.
3. To provide specific information on how to access the various computer systems on which the programs reside.
4. To provide persons with prior computer-terminal experience with exposure to programs they have not yet seen.
5. To provide techniques on how to manipulate computer simulations to assist in understanding human physiology.
6. To provide opportunities for students interested in learning more about computers, computer programming, or authoring computer-based learning experiences.

Computer Systems Available

1. OSU IBM 370/155 (COURSEWRITER)
   Tutorial programs in health sciences (see Red OSU Directory). The CASE simulations are also resident on this system but they require some experience in working up patients.
2. MGH DEC PDP-15 (MUMPS)
   Computer simulations in clinical sciences (see MGH User Manual).
   NOTE: MACMAN is called cardiac Simulation (CSM) on this system.
3. NIH DEC PDP-10(System is multi-lingual)
   MACMAN, MACPUF and MACPEE simulations only.
4. GWU DEC PDP-12(Binary or FOCAL)
   Statistical routines, Game of Life (M2LIFE) and FOCLEARN. Original version of A-CL-COR runs on this processor.
   NOTE: The PDP-12 is occasionally unavailable for time-sharing when used in stand-alone configuration by our neurophysiology unit.
5. GWU DEC PDP-8/E(System is multi-lingual)
   TRMLRN (FOCAL), CELLMB (BASIC), ABCHEM (FOCAL).
   NOTE: since programs are being added to this system at frequent intervals, it is useful to know how to list the directories of the public libraries for both FOCAL and BASIC.

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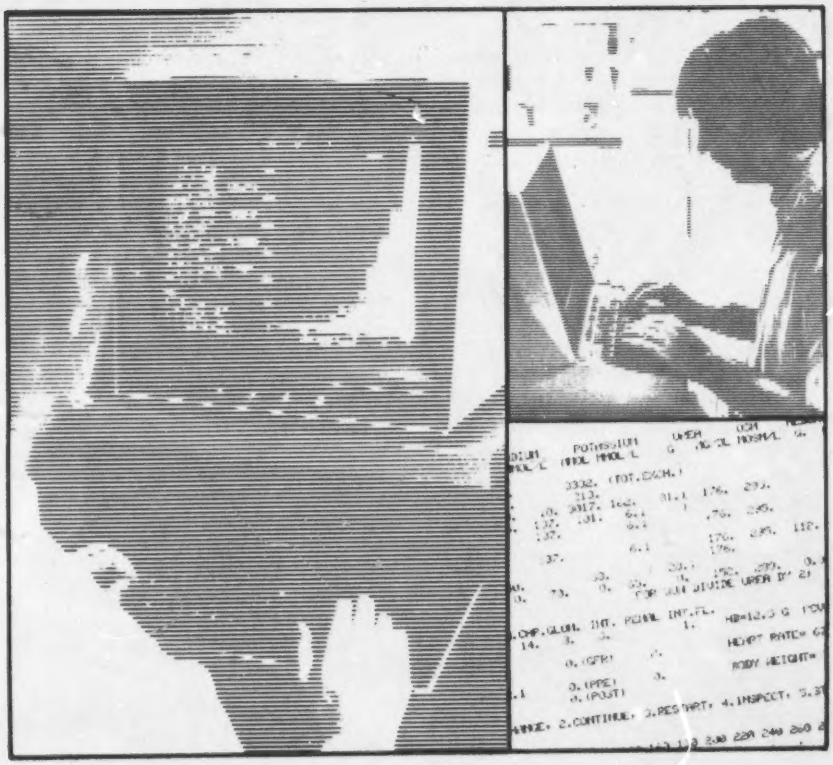


SECTION FOUR - STATE OF THE ART WITH REGARD TO PHYSIOLOGICAL SIMULATION

Chapter Seven

THE ANALOG (COMPUTER) AS A PHYSIOLOGY ADJUNCT *(Part 2)*

Peter A. Stewart

Originally published: *Physiologist* 22(1): 46-47, 1979

A MORE COMPLEX EXAMPLE: CO_2 CONTROL IN THE RESPIRATORY SYSTEM

This example requires non-linear differential equations, and is therefore somewhat more sophisticated than the previous, strictly algebraic example, but the approach and principles are the same. We assume that the reader is familiar with the physiological details, and consider here mainly th process of getting the system on to the analog.

The physiological model is at the level of Grodins' "Respiratory Chemostat", and lumps the many complexities of the respiratory and control systems into 3 compartments plus a control equation. The 3 compartments are the alveolar volume, V_A, the circulating blood, flowing at a constant rate, $\dot{Q}$ and the tissues volume V_T. Control is represented by the linear relationship presented in the previous section. Capillaries are assumed 100% effective, so that alveolar and arterial partial pressures are the same, as are venous and tissue partial pressures; i.e. $P_a = P_A$ and $P_v = P_T$. The CO_2 dissociation curves for the various compartments are approximated, near physiological values, by straight line segments, so that for compartment x we have $[CO_2]_x = S_x \cdot P_x + K_x$ where S and K are constants to be evaluated from the known dissociation curves.

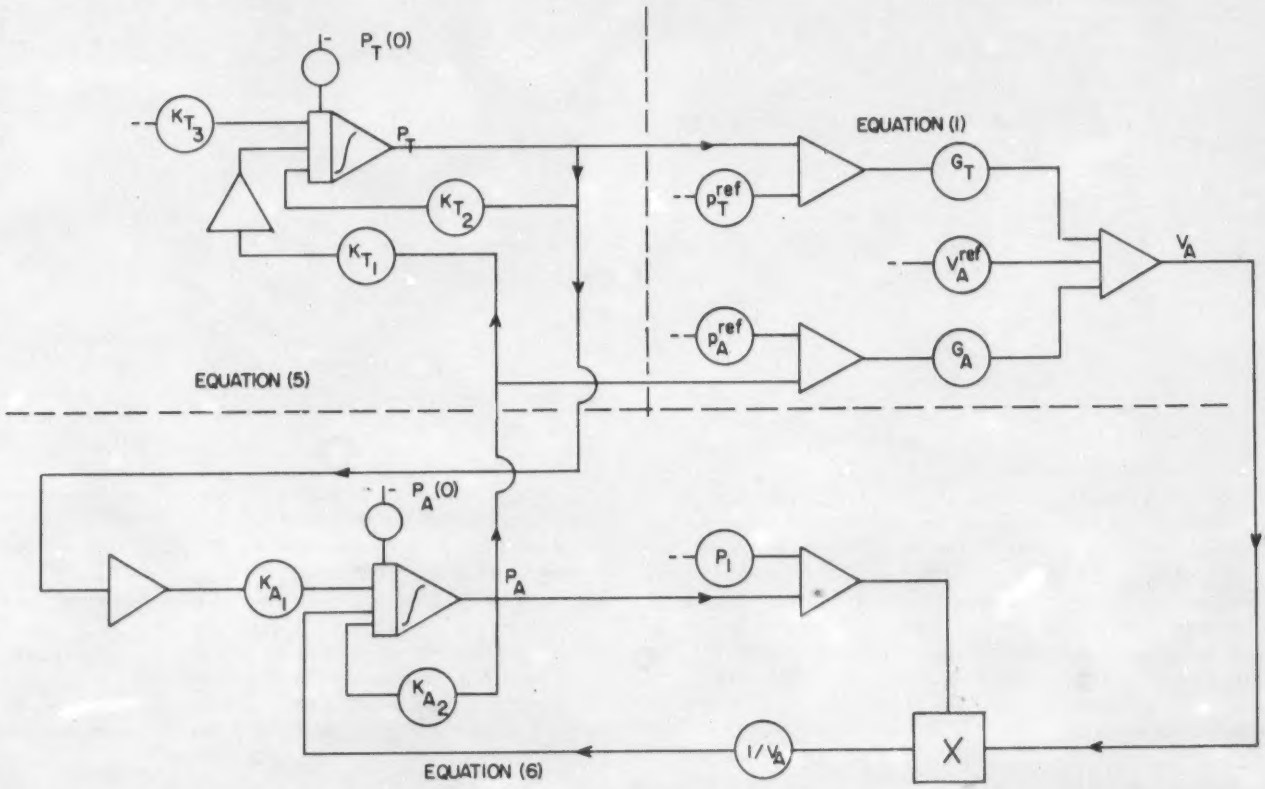
Application of conservation of mass for CO_2 to the tissue and alveolar compartments, after a little rearranging and algebra, then gives these two differential equations:

$$\frac{dP_T}{dt} = \underbrace{\frac{S_a \dot{Q}}{S_v V_T}}_{K_{T_1}} \cdot \underbrace{\frac{\dot{Q}}{V_T}}_{K_{T_2}} \cdot P_A \cdot P_T + \underbrace{\frac{METAB}{S_v \cdot V_T}}_{K_{T_3}} \qquad (5)$$

$$\frac{dP_A}{dt} = \underbrace{BP \cdot S_v \frac{\dot{Q}}{V_A}}_{K_{A_1}} \cdot P_T - \underbrace{BP \cdot S_a \frac{\dot{Q}}{V_A}}_{K_{A_2}} \cdot P_A - \frac{\dot{V}_A}{V_A} \cdot (P_A - P_I) \qquad (6)$$

METAB is the rate of CO_2 production by the tissues, BP = ambient barometric pressure, and P_I the partial CO_2 pressure in inspired air.

The control equation is equation (1) as presented on page 13. Combining constants as indicated, translation of equation (5), (6), and (1) into analog symbols then gives us this diagram.



The scaling problem also exists here, in time as well as in the magnitude of the variables expressed as voltages. For analysis of the system it is very convenient to express all values in terms of minutes, but have them run on the analog as seconds. An hour's response by the body can then be followed in just a minute on the analog. On the other hand, direct comparision with actual body behavior requires scaling seconds as seconds, but this is easily done by re-setting all the pots appropriately.

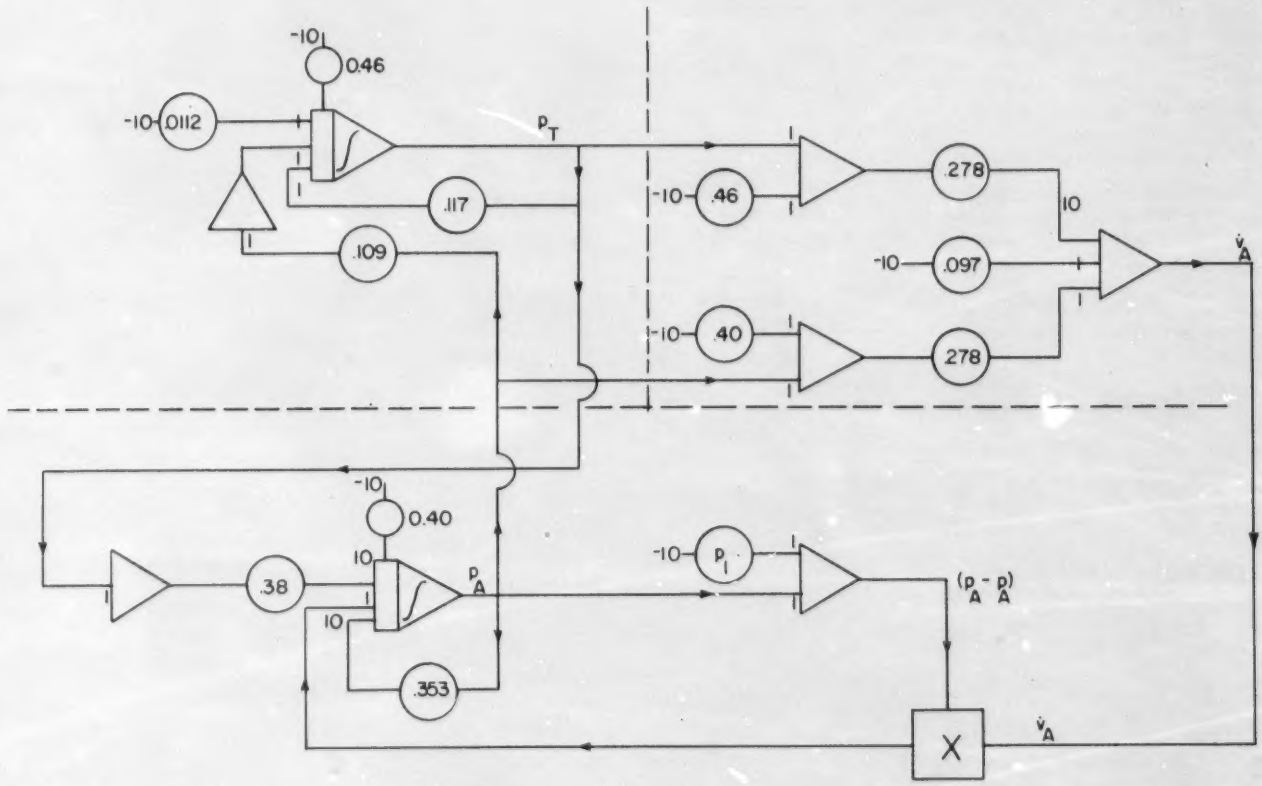
The actual scaled equations, suitable for setting numerical values onto the pots and running in the 1-second-represents-1-minute mode, using body parameters for the writer, and using the same scaling factors as before, are as follows:

$$p_A = 3.80\, p_T - 3.53\, p_A + v_A\,(p_I - p_A)$$

$$p_T = 0.109\, p_A - 0.117\, p_T + 0.112 \qquad (7)$$

$$v_A = 2.78\,(P_T - 4.6) + 0.278\,(p_A - 4.0) + 0.970$$

The scaled analog diagram for this system therefore is:



Once this has been patched, it can be used to make recordings on any polygraph, exactly comparable to direct experimental recordings. One simply takes a lead from the appropriate point on the analog, to the recorder, in place of the lead from the corresponding transducer - pressure gage, spirometer, CO_2 meter, and so. P_I can be changed abruptly by a valve in the gas line to the person or animal, and by a switch in the input representing P_I on the analog, and the responses of the two systems can be compared on the same recorder. With this model, the responses are very close together.

With the analog in front of him, the student can then ask whether he understands the response he sees. Why is the time course exactly what it is? Why are there over-shoots on both the "on" and "off" phase? What physical variables determine the time constants for equilibration of the system to a new P_I value? How will changing blood flow ($\dot{Q}$) alter the form of the responses? The list of inevitable, and with the analog, answerable, and highly instructive, questions is unending.

HARDWARE

In this laboratory, for teaching in both cell and organ system physiology courses, we have used 2 Electronics Associates Incorporated Model TR-20 analog computers with 20 amplifiers, 8 integrators, 3 multipliers, 24 pots and 2 function generators. These units originally (1967) cost about $14,000. Most comparable machines sold today also incorporate analog-digital interface circuitry so they can be used as hybrid, or combination machines. This is highly desirable for research purposes, but unduly complicates their usefulness as simple, easily understandable teaching devices. With a little expertise and handwork a very satisfactory "custom-built" analog can be assembled for a minute fraction of these prices, by connecting up commercially available op-amp chips. In the present era of cheap chips, it probably makes sense, in fact, to assemble a permanent analog configuration for each problem, and mount it in its own "black box" as a rugged unit for student use. For learning about analogs, on the other hand, there is no substitute for the convenience and visibility of the more fancy general machine.

Physiologists who would like to explore analog possiblities, but do not have lavish instructional budgets, should know that many

electrical engineering departments are well equipped in this area, and their equipment is often readily available for learning, practice, and even trial runs with students. This is by far the cheapest and most efficient way to find out just how much hardware you really do need to model the physiological systems of interest to you.

Our experience with the Electronic Associates Inc. (EAI) analog machines has been good. Their current and much improved equivalent to the TR-20 is called "MINIAC", and sells for about $10,000 with comparable hardware to our TR-20's. EAI will respond to telephone inquiries if more detailed information is needed. (Electronic Associates, Inc., 185 Monmouth Pkwy, West Long Beach, NJ 07764. (210) 229-1100)

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Chapter Eight

TEACHING BY SIMULATION WITH PERSONAL COMPUTERS

James E. Randall

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The same technology which has made the pocket calculator an individual possession now has the potential for providing personal computers which can be used for a variety of functions, including self-instruction. Microprocessors, semiconductor memories, economical mass storage devices, and conventional video monitors are being combined into sophisticated computer systems which can be purchased at reasonable prices, even at neighborhood shopping centers. Although these small computers do not have the capacity and speed of large time-shared macrocomputers, their large numbers and convenient accessibility could have considerable impact on the educational system once instructional programs are available. Furthermore, their portability and ability for rapid interaction between the student and machine can provide compensating advantages over those remote terminals which are tethered by telephone lines and which often have limited communication speeds.

This paper describes how a small digital computer can be used to simulate the classic peripheral nerve demonstration in which the action potential responses to pairs of stimuli are used to illustrate the properties of excitable membranes: local response, summation, threshold, refractory period, accommodation, and anode-break excitation. The simulation involves digital solutions of the Hodgkin and Huxley equations (1) which constitute the explanation universally used in textbooks, so the exercise is no more realistic than this model. Graphic and tabular displays do provide the students with information about how the individual conductances change with time as a result of stimuli, how the ionic currents vary, and that these currents add to change the membrane voltage. A major benefit of this simulation over the frog nerve experiment itself is that the student can gain insight regarding the mechanism commonly proposed to explain the action potential. The hardware is sufficiently flexible that models of other physiological processes can be demonstrated as the software programs are developed.

The Computer System

Personal computers have the general size and appearance of an electric typewriter plus television set, or the remote computer terminals seen in many businesses; however, the microcomputers are complete systems and require only an external source of power. A wide variety of small computers are now available but unfortunately the configuration with optimal features for simulation now requires incorporating components from different manufacturers. This is aided by the popularity of the S-100 bus standard, a scheme where different modules use the same connectors and pin assignments. The appendix describes the configuration the author has assembled for graphic simulation of the spike within ten seconds and also an economical version which is adequate for slower tabular presentations. The balance of the present section discusses some of the equipment considerations involved in implementing the action potential example which is described in the following section.

The central part of the computer contains the microprocessor, power supply, and interfacing circuitry for peripheral devices such as a mass storage unit, video monitor, and printer. Integral components should include a sturdy keyboard and circuitry capable of starting up the programs without special technical skills. Within the computer should be memory storage space for between 16K and 32K characters for programs. Additional special circuits may be advantageous as will be discussed below. The printer is not required for the student to use the computer. Unless program listings are required for software development the printer cost, bulk, noise, and mechanical vulnerability weigh heavily against the small advantage of a permanent copy of the exercises.

Video monitors are quite adequate for both graphic and alphanumeric displays. The computer provides modulated voltages to a television raster according to information stored in the memory. This raster sets the limits of vertical resolution while the monitor responsiveness sets the horizontal resolution. Although many computer hobbyists modify television sets for inexpensive displays, slightly better quality video monitors are recommended for their eye-pleasing contrast and legibility of characters. The lecture room used by the author happened to have several large monitors originally used for video cameras. During lecture the simulation was demonstrated to the whole class, then the computer was moved to

the library where the students used it with two small 9 inch monitors.

Many personal computers come with an alphanumeric display capacity of 16 lines of 64 characters which is quite adequate for instructions and tabular simulations. To use this for graphic display of an action potential gives the appearance of plotting by typewriter in that the verticle resolution is limited to 10 mv over the range −120 to +20 mv and time resolution is limited to 0.4 msec over the range 0 to 12. Some computers have graphic capabilities or these may be added; typically, for a resolution of 256 by 256 points, an available feature will be described in the section on graphic simulation of the action potential.

The most economical mass storage medium is the common audio tape cassette upon which program information is coded by an audio frequency signal. Tape recorders are very reliable in the hands of students but the method takes up to 4 minutes to load a program from tape into memory. This is not a serious limitation if one exercise is to be used for an extended period, but it is impractical when many programs are to be run at one sitting. Recent advances in another storage medium, called flexible, or "floppy" disks, now permit loading programs within 10 seconds from a reusable disk costing a very few dollars. The electronic interface and drive motor unit costs less than $1,000 and is a very wise investment if the computer is to be used extensively.

Unfortunately, neither different audio tapes nor different disks are fully interchangeable between units from different manufacturers. The so-called "CP/M" disk operating system seems to be the emerging standard and it is available on 8" IBM format disks and on the popular 5" North Star and Micropolis disks. There are other special system considerations that can be best appreciated after the following description of the simulation program itself.

Action Potential Simulation

Since the Hodgkin-Huxley "space-clamped" model for excitation is one of the most popular quantitative models used in teaching physiology, its simulation can illustrate the features and limitations of personal computers. The reader is referred to the chapter by Dr. Peter Stewart (2), who has used simulation extensively in his teaching at Brown University, for FORTRAN statements which are direct adaptations of the original non-linear differential equations. The Appendix to the present paper lists a version written for BASIC by the author.

In practice the student turns on the computer and loads the program into memory from the mass storage device. Following instructions on the screen specific values can be assigned to stimulus parameters, such as the amplitude and duration of each of two stimuli as well as the time interval separating them. Once these are entered the computer goes through iterative solutions of digital forms of the Hodgkin and Huxley equations, first using the membrane voltage to evaluate the first-order rate constants which determine the rates at which the ionic "on" and "off" factors change from one state to the other. These rates of change operating for a finite time increment establish new values of the membrane conductances and currents; the currents are added, including any stimulating current, and then used to calculate the incremental voltage change. Once the voltage is updated, the process is repeated. Depending upon the objectives of the exercise any combination of the computed variables can be displayed in numerical tables or by graphics for selected iterations.

Figure 1 is a photograph of the video screen showing the questions and responses which might be involved in illustrating the larger stimulus which is needed to evoke a regenerative response during the relative refractory period. By pressing the RETURN key in response to the first question the student has left the initial steady state values of the rate constants and dimensionless variables at those for a resting potential of −90 mv, the value used in this program. To mimic anode-break excitation the initial membrane voltage could have been set to some hyperpolarized value which would have determined the initial Na^+ and K^+ conductances and time constants. The second line on the screen allows the operator to suddenly displace the membrane voltage to some value, and has a "default" value equal to the resting membrane potential.

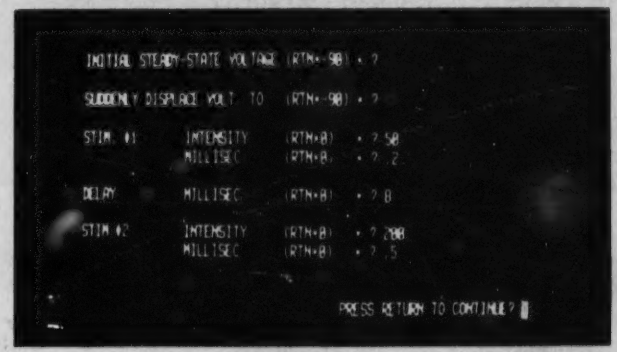
INITIAL STEADY-STATE VOLTAGE (RTN=-90) = ?
SUDDENLY DISPLACE VOLT TO (RTN=-90) = ?
STIM 01 INTENSITY (RTN=0) = ? 50
MILLISEC (RTN=0) = ? .2
DELAY MILLISEC (RTN=0) = ? 8
STIM 02 INTENSITY (RTN=0) = ? 200
MILLISEC (RTN=0) = ? .5
PRESS RETURN TO CONTINUE?

Fig. 1 ***Establishing the conditions to be simulated.*** **The program requires the user to enter the experimental conditions. This is done by answering queries and sending the information to the computer by pressing the 'Return' key. Default values have been stored., e.g. (RTN = −90) to simplify the entry process. Here the membrane is left at the resting potential (−90 mv). No displacement voltage is requested. The first stimulus is given an intensity to 50 units (microamps/sq. cm^2), for a duration of 0.2 millisecond. An 8 millisecond delay is requested. The second stimulus is assigned an intensity of 200 units and applied to a period of 0.5 millisecond.**

The stimulus intensities are in $\mu a/cm^2$ and the durations in milliseconds. The choice of these parameters depend upon the instructor-designed protocol for the exercise. Students like to make a game out of finding the exact threshold stimulus magnitude at which Na^+ and K^+ currents will balance for several milliseconds before one exceeds the other. For measuring the stimulus strength-duration curve the duration can be consistently set to specific values while the amplitude is varied until threshold is found. The time course of the refractory period can be mapped out by varying the duration of the time delay to the second, or test, stimulus looking for its threshold at each time delay. The process of accommodation can be demonstrated nicely by having the conditioning stimulus at a very low amplitude, e.g., 2 units, and long duration, e.g., 8 msec; then at 8 msec the stimulus is increased to a standard threshold value. During the conditioning stimulus it is possible to follow the Na^+ inactivation and increased K^+ conductance so that K^+ current out is able to keep up with stimulating current in. At the time of the test stimulus it takes a very large magnitude to get a regenerative spike.

Figure 2 is a tabular presentation of the membrane conductances, currents, and voltage for the first 2.2 msec after the application of the stimulus amplitude of 50 units for 0.2 msec. The instructive information is contained in the temporal changes in membrane Na^+ and K^+ conductances, the initially greater Na^+ in than K^+ current out so that there is a net accumulation of positive charge inside of the cell. This depolarization enhances the Na^+ conductance change until the driving

force upon that ion is reduced, Na^+ inactivation begins, and K^+ current begins to increase. At the time of 1.6 msec the net current becomes outward (the squid axon data was obtained at temperatures lower than those found in mammalian axons) and thereafter K^+ current out exceeds Na^+ current in unless an unusually large stimulus is applied. The simulation can be stopped at any time by pressing a specific key and continued by pressing another; a third key can be programmed to restart the exercise from the beginning.

Fig. 2 *Tabular presentation of the results of the simulation for the conditions selected in Fig. 1.* Computed values of membrane conductances, individual currents, total membrane current; and membrane electric potential. The values were computed for each 0.04 msec but displayed every 0.2 msec. The screen can display only 16 lines at a time so the column labels must be repeated periodically. The computation can be stopped for study, continued, or reinitialized by pressing specific keys.

Whereas the axon operates in infinitesimal calculus the computer seeks solutions at specific time increments. The choice of iteration and displayed time increments are a compromise between the accuracy of the solution and the total time required to achieve the solution. For Figure Two the computation interval was 0.04 msec, every fifth value of which was displayed. Larger computation intervals lead to spurious oscillations whereas the information rate of 3 sec per displayed line is about right for assimilation of the many variables changing during the peak of the spike. In displaying graphic solutions the time for each iteration becomes very significant and involves both the hardware and software considerations outlined in the next section.

Graphic Display Of The Simulation

Most personal computers do not come with sufficient graphic resolution to present a realistic action potential; furthermore, they handle scientific computations so slowly that the total time for simulating the spike and recovery period is excessive. Figure 3 is a photograph of a simulation for the stimulus parameters indicated in Figure One, where the graphic resolution is 256 by 256 points, obtained by adding a special interface card. This gives a vertical resolution of 1 mv which is quite adequate and still leaves enough space for a display proportional to the stimulating current. The computation increment used was 1/30 millisecond with two sweep display options. A fast sweep, showing 0 to 7.5 msec, displayed every computed point and is useful for observing threshold phenomenon. In order to study the refractory period a slow sweep of 0 to 15 msec displayed every-other computed value for a total of 225 points at displayed increments of 1/15 msec. In principle any of the computed variables can be displayed provided the screen does not become too cluttered; in practice the combination of voltage and stimulus seems to be very effective.

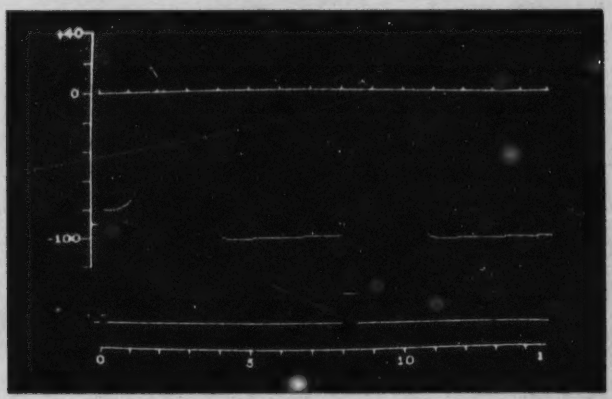

Fig. 3 *Graphic presentation of the results of the simulation for the conditions selected in Fig. 1.* The plot contains, in the upper curve, computed membrane potential in mv versus time in milliseconds; the second curve indicates the time, duration and intensity of the stimuli. Vertical resolution for the membrane potential is 1 mv; for the stimulus intensity is 5 units. Horizontal resolution for the time axis is 1/15 millisecond. The simulation when programmed in BASIC requires 2 - 5 minutes compared with 14 seconds if programmed in machine language using a numerical processor chip such as the AM-9511 (see text).

The time to simulate and display the 7.5 msec sweep can range from 8 sec using machine language and special hardware to as much as 3 min using some versions of BASIC. The time to do one iteration starting from a given membrane voltage, computing conductances and currents and then the new voltage involves such variables as: the microprocessor machine cycle time, the kind of programming language used, the algorithms which evaluate the exponential functions in the H-H equations, and the method of numerical integration of the non-linear equations. Full discussion of each of these is beyond the scope of this paper but it is possible to indicate the most practical places to improve the speed of numerical computations, an important consideration in any simulation.

The most popular 8-bit microprocessors run at either 2MHz or 4MHz for executing individual references to memory, a factor of two; however, the 4MHz versions require more expensive memory and more critical electronics. Machine language programming can run as much as 100 to 1,000 times as fast as does the high-level languages; but, there are several versions of BASIC, the programming language most often supplied with personal computers. The slower versions have the great accuracy required in business accounting by use of binary-coded-decimal (BCD) arithmetic but the total time to display a graphic spike is prohibitive. Versions of BASIC copyrighted by Microsoft, Inc. use a floating point format (analogous to scientific notation); it has sufficient accuracy and executes most functions significantly faster than do the BCD versions. In addition, this format is compatible with a new arithmetic processor chip, the AM-9511, which can perform arithmetic and evaluate transcendental functions with a single machine instruction in a fraction of the time required for the

successive additions and subtractions required of machine language subroutines. It is anticipated that numerical processors will be considered in future versions of both BASIC and FORTRAN so that one can program in the high-level languages and have rapid execution of compiled programs which approach machine language speed and compactness.

Summary

The ability of microcomputers to present graphic displays of dynamic responses of physiological systems coupled with their economy and accessibility may help realize the largely unfilled potential of computer-assisted-instruction, but the real limiting factor will be the extent of the commitment of the participating faculty. Realistic instructional models which require the statement of hypotheses in concise logical terms should advance physiology as a scientific discipline.

Appendix

This section describes a minimal computer system, the author's choice of a desirable configuration using components on the market today, and a listing of the simulation in BASIC.

Much of the promotion of the under-$1,000 computers stresses their potential for games, but one should not overlook their ability to do simulation in tabular form and with limited graphic resolution. One model with a resolution of 48 vertical by 128 horizontal points can compute and display 6 milliseconds of an action potential with a resolution of 3 mv in a total time of 2 minutes. It can be purchased with Microsoft BASIC in a read-only-memory and with an additional 16K of memory for programs, all contained within the keyboard cabinet. This, plus the audio cassette mass storage and video monitor, provides a compact and economical introduction to simulation. Although these small units can be extended to include rapid floating-point processors and high-resolution graphics it seems more appropriate to start with a system larger than this.

There are several models of small computers which incorporate the popular S-100 bus hardware and which can be used with the CP/M disk operating system, two suggested steps toward standardization. The one used by the author was a SOL, manufactured by Processor Technology of Pleasanton, CA, which has a reliable keyboard; an operating system which is activated when the power is turned on; and built-in interfacing for an audio-tape cassette mass storage device, video monitor, external printer, and remote computer access as a terminal. It also has five slots for S-100 bus cards for additional memory and special hardware.

Two of the S-100 slots contained 16K memory each, available from a number of different suppliers. One slot had the interface to the floppy disk, manufactured by Microplis Corporation of Canoga Park, CA. This particular mass storage device stores 143K characters on one 5¼" disk and the drive unit head is removed from the recording surface if not addressed within a fixed time delay. The fourth slot had a 256 by 256 graphics interface card (including 8K of memory) manufactured by Matrox Electronics of Montreal. The remaining bus slot contained the AM-9511 arithmetic processing unit on an interface board manufactured by MemTech Co. of San Diego. Two Sanyo model VM-4209 9" video monitors were used, one for the stimulus parameters and tabular information, the other for the graphics. This total package, costing about $4,000, could be used for simulation of a wide variety of physiological processes and other more general computing applications as well. This technology is changing rapidly and it is possible that the total system may become available from a single manufacturer at lower cost.

The following listing of a program to simulate the Hodgkin and Huxley equations, written in Microsoft BASIC, requires less than 3K of memory beyond the BASIC itself. For clarity it does not include the second stimulus, error messages for unreasonable entries, nor formatting of the computed variables. It is capable of displaying the solutions illustrated in Figure Two at less than 10 seconds per line, depending upon the particular computer being used.

```
10 'HODGKIN-HUXLEY SIMULATION
20 INPUT "STIMULUS AMPLITUDE = ";SA
30 INPUT "STIMULUS DURATION  = ";SD
40 MV=-90:  T=0:  DT=1/25
50 GOSUB 200:              'SET ALPHA, BETA
60 N=AN/(AN+BN):  H=AH/(AH+BH):  M=AM/(AM+BM)
100 'MAIN LOOP  <--------------
110 GOSUB 200              'SET ALPHA, BETA
120 GOSUB 400              'UPDATE G, I, V
130 T=T+DT                 'T=END OF INCREMENT
140 PRINT T; GK; GNA; IK; INA; IL; IT; MV
150 GOTO 100:  '>--------------
200 'CALCULATE ALPHA, BETA FOR V
210 V=-MV-90:              'V=0 AT REST
220 IF V+25=0 THEN V=-25.1
230 IF V+10=0 THEN V=-10.1
240 BN = .125*EXP(V/80)
250 BM = 4*EXP(V/18)
260 BH = 1/(EXP((V+30)/10)+1)
270 AN = .01*(V+10)/(EXP((V+10)/10)-1)
280 AM = .1*(V+25)/(EXP((V+25)/10)-1)
290 AH = .07*EXP(V/20)
300 RETURN
400 'UPDATE CONDUCT, CURRENT, VOLTAGE
410 DN = AN*(1-N)-BN*N:  N=N+DN*DT
420 DM = AM*(1-M)-BM*M:  M=M+DM*DT
430 DH = AH*(1-H)-BH*H:  H=H+DH*DT
450 GK = 36*N*N*N*N:  GNA=120*M*M*M*H
460 IK = GK*(V-12):  INA= GNA*(V+115)
470 IL = .3*(V+10.6):  IT = IK+INA+IL
480 IF T<=SD THEN IT=IT+SA      'ADD STIM
490 V=V-IT*DT:  MV=-V-90
500 RETURN
```

Fig. 4 Hodgkin-Huxley simulation program listing in Microsoft BASIC.

REFERENCES

1. Hodgkin, A.L., and A.F. Huxley. A quantitative description of membrane current and its application to conduction and excitation in nerve. *J. Physiol.* 117:500-544, 1952.
2. Stewart, P.A. The Action Potential. Ch. 8 in: *Engineering Principles in Physiology*. Vol. I. J.H.U. Brown and D.S. Gann, Eds., New York: Academic Press, 1973.

Chapter Nine

A COMPUTER MODEL OF THE CARDIOVASCULAR SYSTEM FOR EFFECTIVE LEARNING

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The following model and its description is presented as a useful teaching tool and also as an example of the ease of developing the differential equations of a physiological system and then solving them through simple numerical integration on a digital computer. The physiological model itself is well-established (1-5, 8). Unlike models using a series of algebraic equations, this implementation, like more complex system simulations solves a set of interacting, possibly non-linear, differential equations. Using the same approach, all sorts of relationships (respiration, neural action potentials, drug dynamics, compartmental mixing) can be handled without developing an analytic solution for the set of equations. Implementation is not restricted to a dedicated computer, a large time-sharing system or the availability of a specialized simulation language. Futhermore, the implementation presented here is interactive; responses from the computer come before the student loses interest.

(The model used is similar to that used by M. N. Levy in a recent review of cardiovascular fundamentals: "The cardiac and vascular factors that determine systemic blood flow." *Circ. Res.* 44:739-747, June 1979).

The interaction between the heart and the peripheral parts of the cardiovascular system must be understood to be able to distinguish between normal and abnormal function. A key variable is the central venous pressure, because this is a major (but not the only) determinant of: (a) the rate of blood flow from the periphery, and (b) the filling of the heart and so rate of flow from the heart. Under steady state conditions, when the venous return equals the cardiac output, the resulting central venous pressure is the "operating point" for the system. The concept of such operating points — in contrast to set-points — is crucial for our understanding of homeostasis. The ultrasimple cardiovascular model described here was designed to aid the development of such understanding and to simulate the effect of various distubances on the cardiovascular system. The cardiovascular response to exercise (reduced arterial resistance) and the compensations needed to provide adequate homeostasis may be simulated, as well as the effect of cardiac weakening (reduced contractitlity) on central venous pressure and cardiac output. The effect on "cardiac output" and "blood pressure" of changing other parameters, such as "blood volume," "venous compliance" and "cardiac compliance," may also be studied. To think only in terms of final steady state responses, rather than considering also the transient pattern of change and its quantitative characteristics, limits functional understanding. The model was designed to give this potentially valuable information for study and contemplation. Finally, the model demonstrates the ease and power of digital simulation of complex physiological systems using easily learned BASIC and a microcomputer. A different kind of information is available from such mathematical models than from mechanical models (6), for although the computer model is less direct and seemingly less real, it is much more precise and flexible.

The model is simple in that only one "heart" is used, and the cardiac output is a linear function of filling volume. Only one vascular pathway is present, and the vasculature is lumped into only one arterial bed and one venous bed. There are no reflexes. However, the basic phenomena are graphically and validly demonstrated. A much more complex model (two non-linear hearts, a pulmonary bed, two parallel vasculatures, and provision for fluid shifts across the capillaries) is valuable for exploring research ideas and concepts in my laboratory, but such a model is cumbersome to use and requires either a very high speed computer or long computing time. On a small microcomputer (Processor Technology SOL with a North Star disk system) this model operates at about real time, is quickly set up, and can be easily "revived" if "killed."

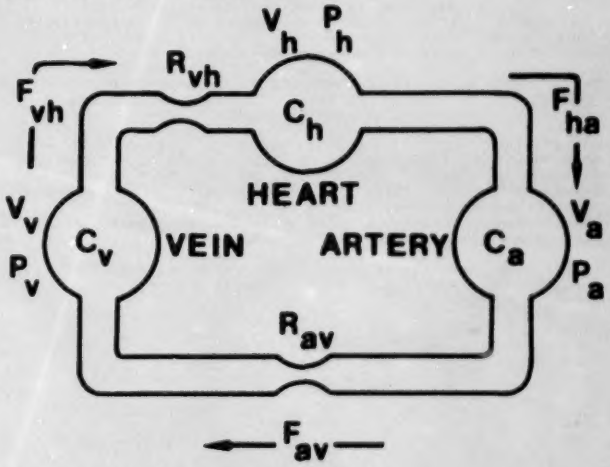

Fig. 1. Schematic diagram of the model.

The model is presented in schematic form in Figure 1. In Figure 2 the assumed Starling, or ventricular performance, relationship of cardiac output (Fha = Flow from heart to arteries) to various end diastolic volumes (Vh = Volume of heart at end of filling) is presented. The 9 interacting equations used to define this dynamic system are described in the Appendix, as is the computer approach to provide an iterative solution to the set of equations.

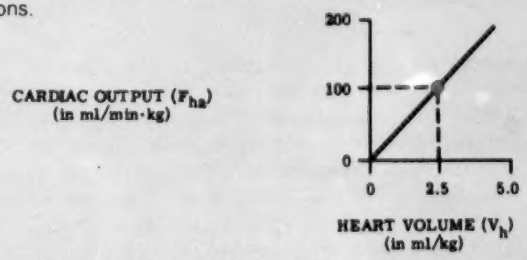

Fig. 2. Relationship between heart volume and cardiac output.

In Figure 3, control conditions and the initial printout are presented. If a printer is available, hard copy of the results can be printed for later study. In the table of "Current Values of Variables and Parameters," note that the total distending blood volume is much less than the total blood volume. The veins, especially at zero transmural pressure, contain a large volume of

blood. At the bottom of Figure 3, a plot of the Guytonian relationship between venous return and cardiac output is presented.

```
RUN

For hard copy output type 1, for video 0 ? 0
Simple Cardiovascular Model  -  CVMDL  -  1978
  C.F.Rothe - Physiology - Indiana Univ., Indianapolis
Integration step size (in minutes) is  .005
Printout is set for 0.1 min intervals.
After changing parameters, continue runs until
  the flows in all 3 segments are equal.
Venous Pressure = ca. Mean Circulatory(capacity vessel) Pres.
Heart  Pressure = Central venous pressure
Distended vasc vol(ml/kg) + unstressed(55) = Total bld volume.
The MODEL has NO REFLEXES or transcapillary fluid compensation
Explore effect of the following - Try various compensations.
 1) EXERCISE - Arterial resistance (Res #1) 40% of normal.
 2) HEART FAILURE - Cardiac Contractility 30% of normal.
 3) HEMORRHAGE - Blood volume decreased 10 ml/kg
                                 Press RETURN to continue
You will be given choices:
  1 - To CONTINUE computing
  2 - To CHANGE parameter values
  3 - To list as PERCENT of control values
  4 - To start over with original control values
  5 - To PLOT cardiac output & venous return vs. R. Atrial Pres
  6 - To QUIT
Use RETURN to ENTER each of your responses.
                                 Press RETURN to continue
T=  0   CURRENT VALUES OF VARIABLES  &     PARAMETERS
SEGMENT       PRESSURE     OUTFLOW    VOLUME   COMPL RESISTANCE
             (mm Hg)    (ml/min-kg) (ml/kg)
-------      --------     --------   ------   ----- -------
01 ARTERIAL    100.00     100.00      4.00      .04      .92
02 VENOUS        8.00     100.00     14.00     1.75      .05
03 HEART         3.00     100.00      2.50      .83      .00
Heart contractile ability = 100.00 % normal
Total blood volume (ml/kg)=  75.50
Vasc distending blood vol.=  20.50 or 100.00% normal
Mean Circ Filling Pressure=   7.8 mmHg

Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6? 5
Flow    Venous Return,R            Cardiac output,O
 240 I                                            *
 220 I                                         O
 200 I                                      O
 180 I                                   O
 160 IR                               O
 140 I      R                      O
 120 I           R              O
 100 I               N - normal operating point
  80 I                  O     R
  60 I                    O          R
  40 I       O                           R
  20 I    O                                 R
   0 I*-----I-----I-----I-----I-----I-----I-----I-----*-----I
R Atrial Pressure 2     3     4     5     6     7     8     9
Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6?  2
```

Fig. 3 Start-up and Normal Conditions.

```
T=  0   CURRENT VALUES OF VARIABLES  &     PARAMETERS
SEGMENT       PRESSURE     OUTFLOW    VOLUME   COMPL RESISTANCE
             (mm Hg)    (ml/min-kg) (ml/kg)
-------      --------     --------   ------   ----- -------
01 ARTERIAL    100.00     100.00      4.00      .04      .92
02 VENOUS        8.00     100.00     14.00     1.75      .05
03 HEART         3.00     100.00      2.50      .83      .00
Heart contractile ability = 100.00 % normal
Total blood volume (ml/kg)=  75.50
Vasc distending blood vol.=  20.50 or 100.00% normal
Mean Circ Filling Pressure=   7.8 mmHg

To make no change type: 0 then RETURN
Change resistance? Type SEGMENT number: 1
New value of RESISTANCE is? .40
Change compliance? Type #: 2
New value of COMPLIANCE is? 1.2
Change CARDIAC CONTRACILITY? (Yes=1,No=0) 1
New value of contractility in % of normal: 250
Change BLOOD VOLUME? (Yes=1,No=0) 0
Shorten print interval to <0.1 min? Yes=1: 0
                 Patience please, computing.
CONTinue computing until outflows about equal.

Time is  .1 minutes                          I # =  20
 SITE          PRESSURE   OUTFLOW   VOLUME
01 ARTERIAL      92.06     199.26     3.68
02 VENOUS        12.35     199.26    14.83
03 HEART          2.39     199.26     1.99
          Total distending volume =  20.50

Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6? 3
T=  .1   CURRENT VALUES OF VARIABLES  &     PARAMETERS
SEGMENT       PRESSURE     OUTFLOW    VOLUME   COMPL RESISTANCE
             (mm Hg)    (ml/min-kg) (ml/kg)
-------      --------     --------   ------   ----- -------
 :* * * Values as percent of control * * *
01 ARTERIAL     92.06     199.26     92.76    100.00    43.48
02 VENOUS      154.43     199.26    105.89     68.57   100.00
03 HEART        79.71     199.26     79.70    100.00   100.00
Heart contractile ability = 250.00 % normal
Total blood volume (ml/kg)=  75.50
Vasc distending blood vol.=  20.50 or 100.00% normal
Mean Circ Filling Pressure=   9.9 mmHg

Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6?  5
Flow    Venous Return,R            Cardiac output,O
 240 I                                            *
 220 I         R       O
 200 I              X - CURRENT VALUE
 180 I            O       R
 160 I          O               R
 140 I        O                   R
 120 I       O                        R
 100 I             N - normal operating point
  80 I    O                                    R
  60 I  O                                        R
  40 I  O
  20 I O
   0 I*-----I-----I-----I-----I-----I-----I-----I-----*-----I
R Atrial Pressure 2     3     4     5     6     7     8     9
Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6? 4
```

Fig. 4 Simulation of exercise with cardiovascular compensation.

An example of changing parameters to mimic exercise is presented in Figure 4. Arterial resistance (Segment 1) is reduced to about 40% of normal; venous compliance (Segment 2) is reduced to about 2/3 of normal to provide Venoconstriction, and cardiac contractility is increased to 250% of normal. A steady state is reached by the next printout (0.1 min) with arterial pressure somewhat less than normal. By choosing option 3, the variables and parameters are presented as percent of control. Even though venous compliance is 2/3 of control, the doubling of blood flow increased the transmural pressure enough to increase the venous (capacity vessel) pressure and volume to a value greater than normal. The central venous pressure operating point is at a value less than control, even with an increase in mean circulatory pressure, because cardiac contractility was greatly increased.

The effect of hemorrhage is shown in Figure 5. The model, just as a living animal, cannot be hemorrhaged instantly. We chose a hemorrhage or transfusion rate to complete the volume change in 0.2 min. Even when the hemorrhage is completed, flows out of the various segments are not equal; about 10 sec is required for the transients to die out. Please remember that the model incorporates no reflexes nor any provision for fluid shifts from the interstitial space into the vasculature. We defined "hypotension" as a blood pressure less than 50 mmHg and "shock" as a cardiac output less than 60 ml/min·Kg. A separate plot of hemorrhaged volume, cardiac output, central venous pressure, and venous return as a function of time will provide clues as to the transient pattern of response of the cardiovascular system. Compensatory mechanisms should be tried and enough information copied to provide a report.

```
To make no change type: 0 then RETURN
Change resistance? Type SEGMENT number: 0
Change compliance? Type 0: 0
Change CARDIAC CONTRACILITY? (Yes=1,No=0) 0
Change BLOOD VOLUME? (Yes=1,No=0) 1
Current TOTAL blood vol=  75.50 DISTENDING vol=  20.50
                    Normal  DISTENDING vol=  20.50
Desired (+ or -) change in volume (ml/kg) is? -10
Shorten print interval to <0.1 min? Yes=1: 1
What interval (in multiples of .005 min)? .020
                Patience please, computing.
CONTinue computing until outflows about equal.

Time is  .02 minutes                          I 0 =  4
 SITE          PRESSURE  OUTFLOW  VOLUME
01 ARTERIAL     96.82     96.59     3.78
02 VENOUS        7.95    111.92    13.84
03 HEART         2.36     78.51     1.88
        Total distending volume =  19.50

Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6? 1

Time is  .04 minutes                          I 0 =  8
 SITE          PRESSURE  OUTFLOW  VOLUME
01 ARTERIAL     87.54     86.75     3.41
02 VENOUS        7.72    112.83    13.38
03 HEART         2.08     69.37     1.70
        Total distending volume =  18.50

Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6? 2
      [Changed print interval & skipped some prints]

Time is  .24 minutes                          I 0 =  48
 SITE          PRESSURE  OUTFLOW  VOLUME
01 ARTERIAL     45.40     44.77     1.85
02 VENOUS        4.21     52.84     7.33
03 HEART         1.57     52.39     1.31
        Total distending volume =  10.50
**** DANGER ***** PATIENT HYPOTENSIVE
**** HURRY *****  PATIENT IN SHOCK !!!!

Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6? 1

Time is  .34 minutes                          I 0 =  68
 SITE          PRESSURE  OUTFLOW  VOLUME
01 ARTERIAL     51.14     51.13     2.05
02 VENOUS        4.10     51.22     7.17
03 HEART         1.54     51.26     1.28
        Total distending volume =  10.50
**** HURRY *****  PATIENT IN SHOCK !!!!

              [ Skipped a printout & chose option 3 ]

T=  .44   CURRENT VALUES OF VARIABLES  &     PARAMETERS
SEGMENT       PRESSURE    OUTFLOW    VOLUME   COMPL RESISTANCE
             (mm Hg)    (ml/min-kg) (ml/kg)
--------     --------    --------    ------   ----- ---------
 ;* * * Values as percent of control * * *
01 ARTERIAL     51.22       51.22      51.22   100.00    100.00
02 VENOUS       51.22       51.22      51.22   100.00    100.00
03 HEART        51.22       51.22      51.22   100.00    100.00
Heart contractile ability = 100.00 % normal
Total blood volume (ml/kg)=  65.50
Vasc distending blood vol.=  10.50 or  51.22% normal
Mean Circ Filling Pressure=   4.0 mmHg

Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6? 5
Flow    Venous Return,R            Cardiac output,O
 240 I                                            *
 220 I                                          O
 200 I                                        O
 180 I                                    O
 160 I                                  O
 140 I                              O
 120 I                            O
 100 I                      N - normal operating point
  80 I R              O
  60 I       R   O
  40 I       O     R
  20 I    O              R
   0 I*-----I-----I-----I-----I-----I-----I-----*-----I
R Atrial Pressure 2     3     4     5     6     7     8     9
Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6?  4
```

Fig. 5 The effect of hemorrhage.

In contrast to hemorrhage, which causes a marked reduction in the venous return curve, cardiac failure causes the cardiac output curve to decrease to low values, even if the central venous (heart filling) pressure is high. Cardiac contractility reduction to 30% of normal with compensatory vasoconstriction, venoconstriction, and transfusion to mimic fluid shifts into the vasculature gave the results shown in Figure 6.

The sensitivity of the cardiovascular system model to changes in various parameters can be explored by plotting cardiac output (as percent of control) against the parameters (as percent of control). An adequate plot will be obtained if 25, 50, 100, 150 and 200% of control parameter values are used. How close are these values to reality, i.e., experimental values? What would be the effect of reflexes and fluid shifts? In many cases, reliable data are not available to test critically even this ultra-simple model.

```
Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6? 2
T=  0   CURRENT VALUES OF VARIABLES  &     PARAMETERS
SEGMENT       PRESSURE    OUTFLOW    VOLUME   COMPL RESISTANCE
             (mm Hg)    (ml/min-kg) (ml/kg)
--------     --------    --------    ------   ----- ---------
01 ARTERIAL    100.00      100.00      4.00     .04      .92
02 VENOUS        8.00      100.00     14.00    1.75      .05
03 HEART         3.00      100.00      2.50     .83      .00
Heart contractile ability = 100.00 % normal
Total blood volume (ml/kg)=  75.50
Vasc distending blood vol.=  20.50 or 100.00% normal
Mean Circ Filling Pressure=   7.8 mmHg

To make no change type: 0 then RETURN
Change resistance? Type SEGMENT number: 1
New value of RESISTANCE is? 1.38
Change compliance? Type 0: 0
Change CARDIAC CONTRACILITY? (Yes=1,No=0) 1
New value of contractility in % of normal: 30
Change BLOOD VOLUME? (Yes=1,No=0) 1
Current TOTAL blood vol=  75.50 DISTENDING vol=  20.50
                    Normal  DISTENDING vol=  20.50
Desired (+ or -) change in volume (ml/kg) is? 5
Shorten print interval to <0.1 min? Yes=1: 0
                Patience please, computing.
CONTinue computing until outflows about equal.

Time is  .1 minutes                           I 0 =  20
 SITE          PRESSURE  OUTFLOW  VOLUME
01 ARTERIAL     87.07     57.17     3.50
02 VENOUS        8.18     41.85    14.39
03 HEART         6.09     60.89     5.10
        Total distending volume =  23.00
**** HURRY *****  PATIENT IN SHOCK !!!!

Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6? 1

Time is  .2 minutes                           I 0 =  40
Time is  .3 minutes                           I 0 =  60
 SITE          PRESSURE  OUTFLOW  VOLUME
01 ARTERIAL     96.49     63.12     3.86
02 VENOUS        9.39     62.62    16.43
03 HEART         6.26     62.56     5.21
        Total distending volume =  25.50

Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6? 3
T=  .3   CURRENT VALUES OF VARIABLES  &     PARAMETERS
SEGMENT       PRESSURE    OUTFLOW    VOLUME   COMPL RESISTANCE
             (mm Hg)    (ml/min-kg) (ml/kg)
--------     --------    --------    ------   ----- ---------
 ;* * * Values as percent of control * * *
01 ARTERIAL     96.49       63.12      96.42   100.00    150.00
02 VENOUS      117.34       62.62     117.36   100.00    100.00
03 HEART       208.53       62.56     208.54   100.00    100.00
Heart contractile ability =  30.00 % normal
Total blood volume (ml/kg)=  80.50
Vasc distending blood vol.=  25.50 or 124.39% normal
Mean Circ Filling Pressure=   9.7 mmHg

Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6? 5
Flow    Venous Return,R            Cardiac output,O
 240 I                                            *
 220
 200
 180 I  R
 160 I        R
 140 I              R
 120 I                    R
 100 I                N - normal operating point
  80 I                                R              O
  60 I                                    O R
  40 I                          O                  R
  20 I          O                                      R
   0 I*-----I-----I-----I-----I-----I-----I-----I-----*-----I
R Atrial Pressure 2     3     4     5     6     7     8     9
Cont:1,Chng param:2,% of control:3,Plot:5,Quit:6? 6
CONTROL IS AT VIDEO TERMINAL
```

Fig. 6 Reduced contractility; with compensation by increased arterial resistance and increased blood volume.

APPENDIX

The model in schematic form is presented in Figure 1.

The equations for the model are:

1) $Fha = Kh \cdot Vhfilled$

The slope of this linear curve with the intercept at zero filling volumes is the "contractility," Kh. Just as the left heart normally buffers the right heart from changes in systemic arterial pressure, the model cardiac output is not directly influenced by arterial pressure. If the "contractility," Kh, is doubled, then twice the outflow occurs at the same filling volume. Note that heart rate is not included. In this areflexic model we assume that the product of heart rate and stroke volume is constant. In real life, compensatory mechanisms tend to maintain the stroke volume with an increased heart rate.

FLOWS through the arterial (Fav) and venous (Fvh) beds are assumed to follow "Ohm's Law," and so are directly proportional to the pressure gradients and inversely proportional to the arterial-to-venous resistance (Rav) and venous-to-heart resistance (Rvh), respectively.

2) Fav = (Pa-Pv)/Rav

3) Fvh = (Pv-Ph)/Rvh

The mean pressure in the heart during diastole (filling) is Ph. In real life there are, of course, many more segments and a pulsatile flow.

PRESSURES at each segment are computed from the definition of compliance (C = ΔV/Δ/P). A linear compliance is assumed. The volume is the volume causing the vasculature to be distended and does *not* include the volume present if the transmural pressure is zero.

4) Pa = Va/Ca (Arterial)

5) Pv = Vv/Cv (Venous)

6) Ph = Vh/Ch (Heart)

The venous pressure (Pv) is the peripheral microvenous pressure and is about the same as the mean circulatory filling pressure. The heart pressure (Ph)is the central venous pressure. A simplifying assumption is that the intrathoracic pressure is zero and so Ph is also the transmural filling pressure of the heart. The "heart" diastolic distensibility (Ch) is assumed to be linear with no limit. "The heart is overdistended" is printed if the diastolic heart volume (both ventricles) exceeds 10 ml/kg.

VOLUMES of each segment, at a given instant, are then computed as the volume at a previous instant plus the integral of inflow minus outflow. Numerically, this integral is merely the difference between inflow and outflow (Fin-fout), at a given iteration, times the time interval (Δt) represented by the iteration.

7) $Va_{(t+\Delta t)} = Va_{(t)} + (Fha-Fav) \cdot \Delta t$

8) $Vv_{(t+\Delta t)} = Vv_{(t)} + (Fav-Fvh) \cdot \Delta t$

9) $Vh_{(t+\Delta t)} = Vh_{(t)} + (Fvh-Fha) \cdot \Delta t$

The logic of these equations is based on the differential equation for conservation of material:

a) $\frac{dV}{dt} = f_{in} - f_{out}$

By definition, dV/dt can be approximated at very small time intervals as:

b) $\frac{dV}{dt} = \frac{\Delta V}{\Delta t} = \frac{V_{n+1} - V_n}{t_{n+1} - t_n}$

Thus, letting $\Delta t = t_{n+1} - t_n$ and converting iteration number to time:

c) $\frac{V_{t+\Delta t} - V_t}{\Delta t} = f_{in} - f_{out}$

And so, at the next iteration (after rearranging Eq. c):

d) $V_{t+\Delta t} = V_t + (f_{in} - f_{out}) \cdot \Delta t$

By making the time interval (Δt) short (e.g., 0.005min), variables do not change appreciably during each iteration. A much longer integration step size (Δt) leads to instability, a much shorter one extends computation time. The following is the heart of the algorithm in BASIC. Values of the variables and the volumes of "blood" in the segments are repeatedly computed by looping back from line 1140 to 970 until the end of the next print interval (T4) is reached.

```
 970  P(1) = V(1)/C(1)
 980  P(2) = V(2)/C(2)
 990  P(3) = V(3)/C(3)
1000  F(1) = (P(1)-P(2))/R(1)
1010  F(2) = (P(2)-P(3))/R(2)
1020  F(3) = K9 * V(3)
1050  V(1) = V(1) + (F(3)-F(1)) * T1
1060  V(2) = V(2) + (F(1)-F(2)) * T1
1070  V(3) = V(3) + (F(2)+F4-F(3)) * T1
1080    V4 = V4 + F4 * T1
1140 IF T9<T4 THEN 970
```

Symbols are:

(1) is the arterial segment, (2) the venous, (3) the heart, P = pressure, V = volume, C = compliance, F = flow, R = resistance, K9 is the cardiac contractility (flow as a function of fiber length), T1 is the integration interval (0.005 min), T9 = the current time, V4 = hemorrhaged blood volume, F4 = hemorrhage rate, and * means multiply.

The computer we use computes with 8 digits of precision, and so truncation errors are minor. This bootstrap method works. Although more elaborate integration routines are available, the simple Euler or rectangular integration is simple yet satisfactory (7) for these models. From a set of differential equations describing the system (such as above), the difference differential equations can be easily developed and solved on a digital computer. Difficult analytical solutions or gross simplifications are not required. The approach works with complex or non-linear differential equations describing physiological functions.

The parameters for "normal" are given in Figure 3. The compliance and distending volumes for each segment are less well established than the values for flow and resistance.

Although the basic equations require only 9 lines of coding, the program is 214 lines long to provide for user information, plotting of the cardiac output and venous return relationships, output of variables and input of changes in parameter values. The model was designed for video (CRO) display with 16 lines of 65 characters each. It is written in BASIC and is available, with suggestions for use, on request from the author. Serious users will document the magnitude and importance of the oversimplification employed and may find ways to improve the model without losing its heurisitic value.

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INSTRUCTIONS TO THE USER

Scan the paper describing the model (1/2 hour).

Ask the instructor to load the program and give help if you get lost or the system malfunctions. RUN the model. Relax. It is hard to kill a computer permanently!
To delete a wrong character, use the DEL key.

As you change parameters, predict the direction and the approximate magnitude of changes of the various variables -- pressure, outflow and volumes. Was your prediction correct? After noting the response from the model, do you understand why the changes occurred the way they did?

Many simplifications have been made. Please report model responses that you feel are not physiologically valid, and explain why. PLEASE REMEMBER:
(a) This model displays NO reflex compensation or transcapillary fluid shifts.
(b) It has no right ventricle or lungs.
(c) The "heart pressure" is the same as the "central venous pressure"; the "venous pressure" is the "mean circulatory filling pressure".
(d) Hemorrhage and transfusion occur at the heart.

Changing parameter values beyond the range of 0.2 to 5 times normal may lead to computational instability.

STUDIES TO EXPLORE (2 hours)

1. EXERCISE (decreased resistance to flow from arteries to veins, [R@1 = .35; about 40% of normal]). Produce compensation (cardiac contractility, and venoconstriction).
2. HEMORRHAGE (try -10 ml/kg) and compensation.
3. CARDIAC FAILURE (try 30% of normal) and make compensatory adjustments.
   (What happens if the blood volume is expanded too much?)
4. Effect of VENOCONSTRICTION (C@2).
5. Effect of decreased MYOCARDIAL DISTENSIBILITY (C@3).
6. Effect of increased RESISTANCE for VENOUS RETURN (R@2).

For an even more detailed understanding, study:

1. The transient response of the flows and pressures following changes in parameters such as hemorrhage or transfusion. (Plot them as a function of time, using the option to change the print interval.)
2. The sensitivity of each VARIABLE to changes in each of the PARAMETERS.

PROGRAM DEFINITIONS

Program Variable	Title	Manuscript Symbol	Unit
C(1)	Arterial Compliance	Ca	(ml/mmHg*kg)
C1(1)	Arterial Compliance, control		"
C(2)	Venous Compliance	Cv	"
C1(2)	Venous Compliance, control		"
C(3)	Heart, Diastolic Distensibility	Ch	"
C1(3)	Heart, Diastolic Distensibility, control		"
F(1)	Arterial Outflow	Fav	(ml/min*kg)
F1(1)	Arterial Outflow, control		"
F(2)	Venous Outflow	Fvh	"
F1(2)	Venous Outflow, control		"
F(3)	Cardiac Output	Fha	"
F1(3)	Cardiac Output, control		"
F4	Hemorrhage or transfusion rate		"
I1	Iteration number		
K7	Cardiac Contractility, control		(ml/min per ml/kg)
K8	Cardiac Contractility, % of control		
K9	Cardiac Contractility	Kh	
P(1)	Arterial Pressure	Pa	(mmHg)
P1(1)	Arterial Pressure, control		"
P(2)	Venous Pressure	Pv	"
P1(2)	Venous Pressure, control		"
P(3)	Heart Filling Pressure	Ph	"
P1(3)	Heart Filling Pressure, control		"
R(1)	Arterial to Venous Resistance	Rav	(mmHg*min*kg/ml)
R1(1)	Arterial to Venous Resistance, control		"
R(2)	Venous to Heart Resistance	Rvh	"
R1(2)	Venous to Heart Resistance, control		"
R(3)	NOT USED		
R1(3)	NOT USED		
T1	Iteration Step	delta t	(min)
T2	Time between printouts		"
T4	Time at next print		
T9	Time, accumulative		
T#	Continue (unique to North Star Basic)		
V(1)	Arterial Distending Volume	Va	(ml/kg)
V1(1)	Arterial Distending Volume, control		"
V(2)	Venous Distending Volume	Vv	"
V1(2)	Venous Distending Volume, control		"
V(3)	Heart Distending Volume	Vh filled	"
V1(3)	Heart Distending Volume, control		"
V	Hemorrhage or transfusion volume		"
V7	Total distending volume, control		
V8	Total distending volume as % of control		
V9	Total distending volume, current		(ml/kg)

Control Variables:
I Options?
I3 Hard copy?
I5 Change blood volume?
I7 Change print interval?
G5, 6, 7, Plot logic variables

Misc:
@7 - Tab for cardiac output
R7 - Tab for venous return
L$ - Segment label string
X - Combination print?
J - Index for segment
I - Index for plot

COMMENTS ABOUT THE PROGRAM

The program is written in North Star BASIC Version 6, Release 5.1.
The BASIC we use is about 13K bytes long. The program now occupies 7311 bytes. It could easily be shortened, if memory is limited, by deleting instructions and some prompts. Each iteration requires about 0.2 sec with a North Star floating point arithmetic board and 0.3 sec without.

The program is organized as:

Line Number	Function
10-90	Hard copy option and Title
100-450	Initial conditions
460-680	Instructions for use
700-960	Printout of parameters and % control
970-1100	MAIN PROGRAM
1130-1270	Printout of results
1280-1710	Choices for parameter changes
1720-2160	Plot routine

North Star BASIC has a few idiosyncrasies that may not be obvious as the program is entered into your system. The comments that follow are by line number:

20 INPUT Most BASICs require a PRINT statment followed by an INPUT statement.

60,70 FILL is to set my computer to output to the printer (pseudo-port 01) rather than to the video port (00) and to input from the printer keyboard. Lines 15-20, 955, 960, 1271-1281 provide the logic for the combination of video and printer use.

290 to 330 and 430,440 These variables are to store the initial conditions for later computing of the percent of control.

350 The integration step size (T1) of 0.005 minutes works. If values are not stable between iterations (variables oscillate), or more accurate computation during transient changes is desired, use 0.001 minute. (If variables go to extremes, a mistake was likely made in coding.)
North Star BASIC uses binary coded decimal to compute to 8 significant digits (about 26 bits). Truncation and round-off errors have been negligible.

590,690 INCHAR$(0) waits for typing a single character, or a carriage return, and assigns it to variable T$. I use it here to stop the printing temporarily to be able to read the stuff on the video screen.

700 North Star BASIC does not have vectored strings such as L$(1), L$(2), etc. and so the variable labels are input here as a single continuous string.

780 The variable label is displayed as part of the string. When J=1, the first through 11th character is printed from L$ using the formula: L$(11*J-10,11*J)

800 &9P2 is the way that North Star BASIC gives formatted output. Here it is 9 characters long with 2 figures to the right of the fixed location decimal point. For models for student use, the display must, I feel, be no more than 3 or 4 significant characters long and, to provide easy comparisons during the runs, must not be in scientific notation (1.45E-2).

```
                * * * * * * * * * * * * * * * *
970 to 1100  THIS IS THE HEART OF THE MODEL
                * * * * * * * * * * * * * * * *
```

1030 To prevent negative flows into the heart this logic is used. In the artery and vein segments flow may indeed be retrograde. Maybe negative arterial or venous flows should be flagged for the user.

1110 Part of the hemorrhaging logic to hemorrhage, transfuse, stop or reverse.
1130 Time update.
1140 Logic for when to print.

1425 and 1480 Compliance and contractility must not be zero. Although the user is warned not to change parameters by more than a factor of 5, you may want to prevent other such changes.

1520 Not all blood volume distends the vasculature and heart. I assume that 55 ml/kg is required to fill the system to a transmural pressure of zero.
Incidentally, I find it much more helpful to normalize volumes and flows to ml/kg of body weight than to follow the clinical practice of normalizing to a square meter of never-measured body surface area.

1590 Here the hemorrhage or transfusion rate is set:
P4 = 5 ^ V
Where: V is volume in ml/kg and F4 is flow in ml/kg-min. The '5' is in reciprocal minutes so that hemorrhage or transfusion, whatever the magnitude, is completed in 1/5 minute. Very fast, but not instantaneous. You may want to change it.

1720 The equations for the plot. This routine was harder to put together than the model!

PROGRAM LISTING

```
10 REM CVMDL Revision 1-April-1980
15 PRINT "If printer available, choose 'combo' and then, when desired,"
16 PRINT "   printout results previously displayed on the screen."
20 INPUT "For video, ENTER: 0    For printer 1/O: 1    For combo: 2 ? ",I3
26 INPUT "Skip explanation printout? No=1  Yes=4 ",I
30   IF I3<>1 THEN 80
40   PRINT "CONTROL AT PRINTER - (UCase:Rpt-EX 2A04 to return)"
50   PRINT "     "
60   FILL 51207,01
70   FILL 51206,01
80 PRINT "Simple Cardiovascular Model  -  CVMDL  -  1978/80"
90 PRINT "  C.F.Rothe - Physiology - Indiana Univ., Indianapolis"
100 DIM L$(35)
110 P(1)=100
120 P(2)=100
130 P(3)=100
140 R(1)=100
150 P(2)=8
160 P(3)=3
170 K9=40
180 R(1)=.92
190 R(2)=.05
200 REM R(3) is not applicable and so is set to .00001
210 R(3)=.000001
220 V(1)= 4.0
230 V(2)=14.0
240 V(3)= 2.5
250 C(1)=0.04
260 C(2)=1.75
270 C(3)=0.8333
280 FOR J = 1 TO 3
290 F1(J)=F(J)
300 P1(J)=P(J)
310 V1(J)=V(J)
320 R1(J)=R(J)
330 C1(J)=C(J)
340 NEXT J
350 T1=0.005
360 T2=0.1
370 V=0
380 T4=0
390 T9=0
400 I=0
410 I1=0
420 V9=V(1)+V(2)+V(3)
430 V7=V9
440 K7=K9
450   IF I=4 THEN 700
460 PRINT "Integration step size (in minutes) is ",T1
470 PRINT "Printout is set for 0.1 min intervals."
480 PRINT "After changing parameters, continue runs until"
490 PRINT "  the flows in all 3 segments are equal."
500 PRINT "Venous Pressure = ca. Mean Circulatory(capacity vessel) Pres."
510 PRINT "Heart  Pressure = Central venous pressure"
520 PRINT "Distended vasc vol(ml/kg) + unstressed(55) = Total bld volume."
530 PRINT "The MODEL has NO REFLEXES or transcapillary fluid compensation."
540 PRINT "WITH REFLEXES, cardiac output is likely increased by heart rate"
550 PRINT "  increases rather than by increased filling and stroke volume"
560 PRINT "TO BE ABLE TO NOTICE THE EFFECT OF EACH PARAMETER CHANGE"
570 PRINT "    Change only ONE parameter at a time."
580 PRINT "                                    Press RETURN to continue"
590 T$=INCHAR$(0)
600 PRINT "You will be given choices:"
610 PRINT "  1 - To CONTINUE computing"
620 PRINT "  2 - To CHANGE parameter values"
630 PRINT "  3 - To list as PERCENT of control values"
640 PRINT "  4 - To start over with original control values"
650 PRINT "  5 - To PLOT cardiac output & venous return vs. R. Atrial Pres"
660 PRINT "  6 - To QUIT"
670 PRINT "Use RETURN to ENTER each of your responses."
680 PRINT "                                    Press RETURN to continue"
690 T$=INCHAR$(0)
700 L$="01 ARTERIAL02 VENOUS  03 HEART   "
710 PRINT "T= ",T9,"   CURRENT VALUES OF VARIABLES  &     PARAMETERS"
720 PRINT "SEGMENT      PRESSURE     OUTFLOW    VOLUME  COMPL RESISTANCE"
730 PRINT "              (mm Hg)    (ml/min-kg) (ml/kg)"
740 PRINT "--------     --------     --------   ------  ----- --------"
750   IF I<>3 THEN 770
760 PRINT " ;* * * Values as percent of control * * *"
770 FOR J = 1 TO 3
780 PRINT L$(11*J-10,11*J),
790   IF I<>3 THEN 830
800 PRINT %9F2,100*P(J)/P1(J),100*F(J)/F1(J),100*V(J)/V1(J),
810 PRINT %9F2,100*C(J)/C1(J),100*R(J)/R1(J)
820 GOTO 840
830 PRINT %9F2,P(J),F(J),V(J),C(J),R(J)
840 NEXT J
850 PRINT "Heart contractile ability = ",%6F2,100*K9/K7," % normal"
860 PRINT "Total blood volume (ml/kg)= ",%6F2,55+V9
870     V8=100*(V9/V7)
880 PRINT "Vasc distending blood vol.= ",%6F2,V9," or ",V8,"% normal"
890 PRINT "Mean Circ Filling Pressure= ",%5F1,V9/(C(1)+C(2)+C(3))," mmHg"
900 PRINT
910   IF I3<>1 THEN 950
920 PRINT
930 PRINT
940 PRINT
950   IF I=2 THEN 1340
955   IF X=1 THEN 1210
960   GOTO 1270
970 P(1)=V(1)/C(1)
980 P(2)=V(2)/C(2)
990 P(3)=V(3)/C(3)
1000 P(1)=(P(1)-P(2))/R(1)
1010 P(2)=(P(2)-P(3))/R(2)
1020 P(3)=K9*V(3)
1030   IF P(3)>0 THEN 1050
1040   P(3)=0
1050 V(1)=V(1)+(F(3)-F(1))*T1
1060 V(2)=V(2)+(F(1)-F(2))*T1
1070 V(3)=V(3)+(F(2)+F4-F(3))*T1
1080 V4 = V4 + F4*T1
1090 V9=V(1)+V(2)+V(3)
1100 I1=I1+1
1110   IF ABS(V4) < ABS(V) THEN 1130
1120   F4=0
1130 T9=T9+T1
1140   IF T9<T4 THEN 970
1150 PRINT "Time is ",T9," minutes                    I = ",I1
1160 PRINT " SITE          PRESSURE  OUTFLOW  VOLUME"
1170 FOR J=1 TO 3
1180 PRINT L$(11*J-10,11*J),%10F2,P(J),F(J),V(J)
1190 NEXT J
1200 PRINT "          Total distending volume = ",%6F2,V9
1210   IF F(1)>20 THEN 1215
1213   PRINT "DEATH IMMINENT!! - (To start over enter: 4)"
1215   IF F(1)<250 THEN 1218
1216   PRINT "RUPTURED ARTERY LIKELY!! (To start over type:4)"
1218   IF V(3)<10 THEN 1230
1220 PRINT "**** WARNING **** HEART IS OVERDISTENDED !!!"
1230 IF P(1)>50 THEN 1250
1240 PRINT "**** DANGER ***** PATIENT HYPOTENSIVE   "
1250 IF F(1)>60 THEN 1270
1260 PRINT "**** HURRY ***** PATIENT IN SHOCK !!!!"
1270 PRINT "     "
1271   IF I3<>2 THEN 1280
1272   IF X=1  THEN FILL 51207,00   \REM To reset I/O port to screen
1273   IF X=1 THEN 1280
1274 INPUT "Printout previous results? Yes=1 ",X
1275   IF X<>1 THEN 1280
1276   FILL 51207,01
1277   PRINT
1278   PRINT
1279   ON I GOTO 710,710,710,710,1760,1280
1280 INPUT "Cont:1,Chng param:2,& control:3,Restart:4,Plot:5,Quit:6? ",I
1281    X=0
1290    IF I>6 THEN 1280
1300   IF I3=1 THEN 1320   \REM FOR HARDCOPY AT PRINTER
1310    ON I GOTO 1680,710,710,110,1760,2130
1320   ON I GOTO 1680,1340,710,110,1760,2130
1330 PRINT
1340 PRINT "To make no change type: 0 then RETURN"
1350 INPUT "Change resistance? Type SEGMENT number: ",J
1360   IF J=0 THEN 1400
1370   IF J=3 THEN PRINT "There is no resistance to cardiac outflow"
1375   IF J=3 THEN 1400
1380 INPUT "New value of RESISTANCE is? ",R
1390   R(J)=R
1400 INPUT "Change compliance? Type 0: ",J
1410  IF J=0 THEN 1440
1420 INPUT "New value of COMPLIANCE is? ",C
1425   IF C>.005 THEN 1430
1426   PRINT "Too stiff. Please choose a higher compliance value"
1427   GOTO 1420
1430 C(J)=C
1440 INPUT "Change cardiac CONTRACTILITY? (Yes=1, No=0) ",K8
1450   IF K8=0 THEN 1500
1460 INPUT "New value of contractility in % of normal: ",K8
1470   IF K8 > 0.001 THEN 1490
1480   K8=0.00001
1490 K9 = K7*(K8/100)
1500 INPUT "Change BLOOD VOLUME? (Yes=1,No=0) ",I5
1510   IF I5=0 THEN 1595
1520 PRINT "Current TOTAL blood vol= ",%6F2,V9+55," DISTENDING vol= ",V9
1530 PRINT "                          Normal  DISTENDING vol= ",%6F2,V7
1540 V4=0
1550 INPUT "Desired (+ or -) change in volume (ml/kg) is? ",V
1560   IF V9+V > 0 THEN 1590
1570   PRINT "THIS AMOUNT OF HEMORRHAGE IS LETHAL ! !"
1580   GOTO 1550
1590 F4=5*V
1595 PRINT "Interval between printouts of data = ",T2," min."
1600 INPUT "Change print interval? Yes=1 ",I7
1610   IF I7<>1 THEN 1650
1620   INPUT "What interval (in multiples of .005 min)? ",T2
1630   IF T2<.5 THEN 1650
1640   T2=0.5
1650 I=1
1660 PRINT "                    Patience please, computing."
1670 PRINT "CONTinue computing until outflows about equal."
1680 PRINT "     "
1690 T4=T4+T2
1700   GOTO 970
1710 REM PLOTTING ROUTINE STARTS HERE
1720 REM  CO = F3 = K9*V3  and  V3 = C3*P3
1730 REM  P3 = F3/K9*C3
1740 REM  VR = F2 = (P2-P3)/R2
1750 REM  P3 = P2-R2*F2
1760 PRINT "Flow    Venous Return,R           Cardiac output,O  Time= ",T9
1770 PRINT " 240 I                                              "
1780 FOR I = 22 TO 2 STEP -2
1790 R7 = 6 + 6*(P(2)-10*I*R(2))
1800 R7 = INT(R7+.5)
1810 O7 = 6 + 6*(10*I/(K9*C(3)))
1820 O7 = INT(O7+.5)
1830 IF I  = 10 THEN 2060
1840                 G7=1
1850 IF R7 < 6  THEN G7=2
1860 IF R7 > 62 THEN G7=3
1870                 G6=0
1880 IF O7 < 6  THEN G6=3
1890 IF O7 > 62 THEN G6=6
1900   G5=G6+G7
1910 IF O7=R7   THEN G5=10
1920 IF G5<>1   THEN 1950
1930 IF O7<R7   THEN G5=11
1940 IF O7>R7   THEN G5=12
1950 ONG5GOTO 2040,2000,2000,2020,2040,2040,2020,2040,2040,2080,1980,1960
1960 PRINT %4I,10*I," I",TAB(R7),"R",TAB(O7),"O"
1970   GOTO 2090
1980 PRINT %4I,10*I," I",TAB(O7),"O",TAB(R7),"R"
1990   GOTO 2090
2000 PRINT %4I,10*I," I",TAB(O7),"O"
2010   GOTO 2090
2020 PRINT %4I,10*I," I",TAB(R7),"R"
2030   GOTO 2090
2040 PRINT %4I,10*I," I"
2050   GOTO 2090
2060 PRINT %4I,10*I," I",TAB(24),"N - normal operating point"
2070   GOTO 2090
2080 PRINT %4I,10*I," I",TAB(O7),"X - CURRENT VALUE"
2090 NEXT I
2100 PRINT "    0 I*-----I-----I-----I-----I-----I-----I-----I-----*-----I"
2110 PRINT "R Atrial Pressure 2     3     4     5     6     7     8     9"
2120 GOTO 1271
2130 PRINT "CONTROL IS AT VIDEO TERMINAL"
2140 FILL 51207,00
2150 FILL 51206,00
2160 END
```

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Chapter Ten

COMPUTER SIMULATION IN THE PHYSIOLOGY STUDENT LABORATORY*

S. Katz, R.G. Hollingsworth, J.G. Blackburn and H.T. Carter

Originally published: *Physiologist* 21(6): 41-44, 1978.

Medical colleges in general and physiology departments specifically are concerned with the rising costs of conducting teaching laboratories as well as the decreasing interest of students in laboratory exercises. This concern also expressed by others (3,5,11) led to a search for some means to increase the return on our investment as well as to reinforce the laboratory and ensure that more of the students derive maximum information from each exercise.

For the past several years computers have been used for educational purposes in the health sciences (3,4,6,8) not always taking advantage of their full potential (5). This condition has improved recently as useful applications have begun to appear (7,11,12). It appeared to us that a combination of computers and available, standard laboratory equipment could provide a ready solution to the problem.

Physiological simulations have been implemented for research purposes on analog, hybrid, and digital computers. For research, primary goals in such implementations are usually speed of execution and quantitative reliability. Skilled professionals are required in order to write models and program the appropriate computers. In a teaching environment the goals are somewhat changed. Simulated data need not precisely match laboratory findings, rather, trends are of prime importance. The instructor/machine and student/machine interfaces require careful thought and design. Implementations using digital methods for simulation tend to provide more flexibility for the human/machine interactions than analog methods (1). While digital integration is slower than analog integration, the digital techniques can be programmed in algebraic-like constructs. Descriptions used to represent the physiological models can be presented in a manner which approximates traditional teaching methods. Textual information can be manipulated and provided to the student. The increasing use of BASIC, and other high level programming languages provides instructors with a tool which can be mastered in a matter of days. The language encourages direct, hands-on development of teaching units by instructors, a situation which should improve the quality of teaching.

*Supported by Grant #94/75B, Natl. Fund for Med. Education.

The text that follows describes a preliminary attempt to develop efficient, low cost, computer-based instruction for the physiology laboratory. The system was designed to provide dynamic student/machine interaction potentially capable of illustrating the more sophisticated concepts of Physiology.

Instrumentation and the Model

Equipment layout is diagrammed in Figure 1A and equipment is listed in Appendix I. The computer is located nearby but remote from the student laboratory. The student obtains instructions and questions via the video screen and graphics via the polygraph. Information is entered into the computer via the terminal keyboard.

Several different examples were considered (3,11,13) until it was decided to use a mathematical model of arterial pressure (2). In this model the systemic circulation is represented by a single compartment followed by a series resistance, often referred to as a "Windkessel" model of the circulation (Figure 1B). In this model, blood flows into and out of a variable volume compartment, having a variable compliance and outflow resistance. The heart is represented by an algebraic flow generator. Flow at any time depends upon heart rate, stroke volume, and aortic competence.

A unique feature of this approach to the computer assisted laboratory is that we are using a polygraph (Grass Model 7) as one of the major display devices. This is a piece of equipment very often found not only in our own, but in other physiology student laboratories and is a tool that students are familiar with and use for a variety of exercises, and demonstrations. The polygraph is under computer control. Relays in the computer, a PDP-12 manufactured by the Digital Equipment Corporation, are opened or closed under program control to turn the polygraph chart drive off and on. Digital values generated in the computer are converted into analog signals, which are fed to the preamplifiers of the polygraph.

Model simulation is coded in ANSI FORTRAN IV and runs under the OS/8 operating system (10). The programs could be written just as easily in any other high level language e.g. BASIC, that utilized simple function calls involving devices like A/D converters, clocks, etc. enabling easy interfaces to be developed to the computer and common laboratory equipment. An additional advantage to using FORTRAN was that

several models have already been written in that language (8,9). This could allow a variety of simple programs and different types of physiological simulations to be made available at the laboratory student station.

An inexpensive video terminal (Digilog) is used as the console device at the student station located 100 feet away from the controlling computer and operates at 300 baud. Hardcopy output of the model is displayed on the Grass polygraph with the signals being supplied by the computer's D/A converters. Since the polygraph contains a remote chart drive option it can be turned on and off and various speeds may be selected using the computer relays. Instructions for connecting the hardware and running the program are given in Appendix II.

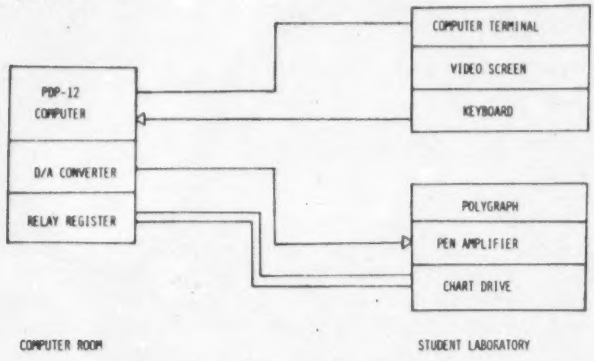
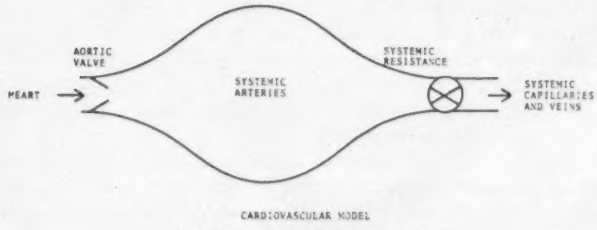


Fig. 1 A. Block diagram of hardware



B. Systemic circulation model

Use of the Model in the Student Laboratory

Instructional use of the simulation in the student laboratory can be extremely flexible. Initial trials with the model involved a class of 55 dental students who were taking an arterial pressure/electrocardiography laboratory as part of their coursework in physiology. We have since utilized the same simulation with a class of 165 medical students. In each case the students were divided into groups of 3-6 people and assigned to terminal/polygraph station on a rotating basis on the afternoons during which the traditional 3-4 hour laboratory was underway. In this manner both a traditional exercise and a simulation exercise was completed by each group.

In all cases the students are introduced to the program by a short instruction section. Each group calibrates the polygraph before beginning the exercise. Instead of calibrating the polygraph itself the student utilizes a feedback loop involving the terminal, computer and polygraph. Calibration is accomplished by using the terminal to request the computer to send to the polygraph signals representing 0 and 100 mm of Hg. The student then presses "U" and "D" keys on the terminal keyboard to move the 0 and 100 mmHg lines to the appropriate positions on the chart paper. A typical calibration is shown in Figure 2. This procedure eliminates time consuming instruction on polygraph usage and allows more time for discussion of program content.

```
          POLYGRAPH CALIBRATION

 THE CHART WILL START WITH THE
 PEN AT 0 MM HG.   IN ORDER TO MOVE
 THE PEN TO THE NEAREST HEAVY LINE, PRESS
 THE U (UP) AND D (DOWN) KEYS AND THE
 RETURN KEY.   TYPE DONE AND PRESS THE
 RETURN KEY WHEN FINISHED.
DONE

  THE CHART WILL NOW START WITH THE
 PEN AT 100 MM HG.   REPEAT THE
 CALIBRATION PROCEDURE SO THAT THE PEN
 IS NOW 2 CM (4 HEAVY LINES) ABOVE
 THE ZERO LEVEL
U
U=UP, D=DOWN, DONE=FINISHED
U
U=UP, D=DOWN, DONE=FINISHED
U
U=UP, D=DOWN, DONE=FINISHED
U
U=UP, D=DOWN, DONE=FINISHED
U
U=UP, D=DOWN, DONE=FINISHED
DONE

  THIS COMPLETES THE CALIBRATION.
 EACH MM OR SMALL CHART DIVISION EQUALS
 5 MM HG.

PRESS THE RETURN KEY TO CONTINUE.
```

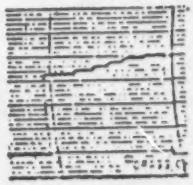


Fig. 2 Polygraph calibration. Insert: polygraph output

Effective student/model interaction is provided by another FORTRAN program that provides each group with an unknown arterial pressure tracing followed by a normal tracing. The group is then asked to reconstruct the unknown tracing by manipulating the different parameters. The calculations for each simulation require about 4 sec. Each arterial pressure plot is made for five cardiac cycles. These may be plotted in real time or time scaled in conjunction with selection of appropriate chart speeds. A detailed description of program operation has been given previously (7). The unknowns represent conditions of arteriosclerosis, valvular regurgitation, exercise, anemia, and hemorrhagic shock. Initial trials utilizing this approach allowed a change in one parameter at a time, each resulting in an alteration in the arterial pressure waveform. The group is asked to identify the condition and determine the parameters associated with their particular unknown. An example of video screen display and graphic output resulting from an input change in heart rate is shown in Figures 3 and 4. At the present time a parameter change beyond the accepted abnormal physiological range is not rejected. Future plans include a rejection of an abnormally high or low value, a message explaining the rejection and a request to enter a new value. In addition an index of valve competence will be added to the list of variables. Further plans will automatically record in a file each change made by the group so that an instructor can review the approaches taken by the students. A record of which student groups have used the module will also be maintained.

The student/model interaction and waveform display are dynamic since new tracings are generated each time parameters are changed. The pressure tracings are plotted in much the same manner as in experiments using live subjects. In this case, however, the polygraph starts and stops under computer control, and the waveform is the result of the manipulation of the mathematical algorithm.

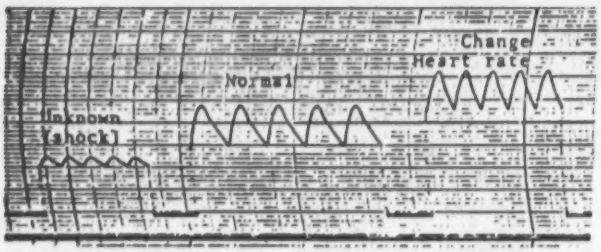


Fig. 3 Polygraph output of arterial pressure for simulation of hemorrhagic shock.

```
                ARTERIAL BLOOD PRESSURE SIMULATION

WHAT IS YOUR GROUP NUMBER?
3

AN ARTERIAL PRESSURE CURVE REPRESENTING
AN UNKNOWN CONDITION WILL NOW BE PLOTTED.

THE CHART WILL BEGIN PLOTTING IN ABOUT 5 SECONDS

THE NEXT CURVE REPRESENTS NORMAL
THE CHART WILL BEGIN PLOTTING IN ABOUT 5 SECONDS

WHAT PARAMETER WOULD YOU LIKE TO CHANGE,
HR,SV,TPR,C, OR VA?
HR
HEART RATE (HR)
  72.00 BEATS/MINUTE

ENTER THE NEW VALUE IN BEATS/MINUTE
100
THE CHART WILL BEGIN PLOTTING IN ABOUT 5 SECONDS

HEART RATE (HR)
  100.00 BEATS/MINUTE
STROKE VOLUME (SV)
   70.00 ML
TOTAL PERIPH. RESISTANCE (TPR)
    1.20 MM HG X SEC/ML
COMPLIANCE (C)
    1.00 ML/MM HG.
VALVE COMPETENCE INDEX (VA)
    1.00
```

Fig. 4 Video terminal display for arterial pressure simulation. The unknown for group 3 is hemorrhagic shock. Information input by student is underlined.

Discussion

Our chief objective was to simulate as closely as possible the learning situation in the laboratory. The importance of an approach like this is emphasized as faculty effectiveness in the laboratory is diluted by larger class sizes and crowded schedules to the point that many of the results and their interpretation may not be discussed. For the same reasons some students may not even have the opportunity to experience a "hands on" experiment.

The particular model discussed here represents an elementary cardiovascular system but complex enough to illustrate the arterial pressure changes seen in many pathological states. It is presented without any of the feedback systems, e.g., baroreceptor regulation. This limits the model's ability to predict some physiological responses; however its use has proven to be helpful in presenting the physiology of the direct effects of alterations in heart rate, arterial compliance, etc., to students in physiology core courses in dentistry and medicine.

Those students using the model responded very enthusiastically. The approach had all the elements of a "game" and created an atmosphere for dynamic group discussion. This resulted in an in depth exploration of the factors involved in the determination of arterial pressure to a greater extent than that seen in the traditional laboratory. Faculty response was also positive since the method proved to be a useful adjunct to enhance a student's knowledge. Added benefits are envisioned for the future if these programs could be carried out on a self-paced basis, freeing faculty to concentrate teaching efforts on problem areas for which they had no time previously.

A major objection is that our minicomputer handles only one group at a time and the cost of duplication would be prohibitive as shown in an earlier paper by Randall (this issue). With the introduction of reliable, low cost microcomputers this situation is changing significantly. The model discussed here could be designed to run on a microprocessor based system at a cost probably not exceeding $2,000.00 (See Appendix 3). Furthermore, maintenance costs for a system like this would be insignificant. A hybrid system composed of a small analog section would be ideal. More complex models involving a greater number of integration steps could be made available to students at a variety of levels in health science education.

This innovative method of supplementing the physiology laboratory by blending modern educational technology, computers and standard laboratory equipment should be viewed as an initial approach. As a result of this project we are convinced that computer simulation of physiology experiments can provide learning experiences that would not otherwise be available because of cost or time.

It is our observation that where simulations are used in this manner, the student, in a sense, designs the experiment, reacts dynamically to the results, and then makes conclusions on that basis. It is apparent that adjuncts to the physiology laboratory of this kind are capable of making a valuable contribution and may provide a basis to combat the current trends which are decreasing student exposure to laboratory methods.

APPENDIX 1

The simulation is presently operational using the following hardware:

A. PDP-12 Computer System*	
16K words core memory	
Dual LINC Tapes	
256K word disk file	
3 channels D/A converters	
6 programmable relays	$70,000.00
B. Grass Model 7 Polygraph**	
1 channel 7 D/A Amplifier	
1 pen oscillograph	2,500.00
C. Digi Log Telecomputer II Terminal***	
with 12" cathode ray tube	1,950.00
TOTAL	$74,450.00

*DEC
Maynard, MASS. 01754
**Grass Instrument Company
Quincy, MASS. 02169
***Digi Log Systems, Inc.
Babylon Road
Horshaw, PA 19044

APPENDIX 2

Instructions for connecting the hardware components.

1. Connect line from Digi Log terminal to computer console control slot (in back of computer)
2. Connect analog lines #1 and #2 from polygraph remote to computer relay #1
3. Connect analog line from D/A (jack #1) to polygraph (J5 input) – See Fig. below.

Instructions for starting program.

1. System tape should be loaded (OS-8/12 with FRTS·SV included)
2. Type: CTRL(C). A period indicates that OS8 is loaded.
3. Mount tape with FORTRAN IV in unit Ø and program tape on Unit 1.
4. Type: SU CVLAB/Q
5. Type: (CR)
6. Type: (CR)
7. Type: (CR)
8. Type: SU CV/Q

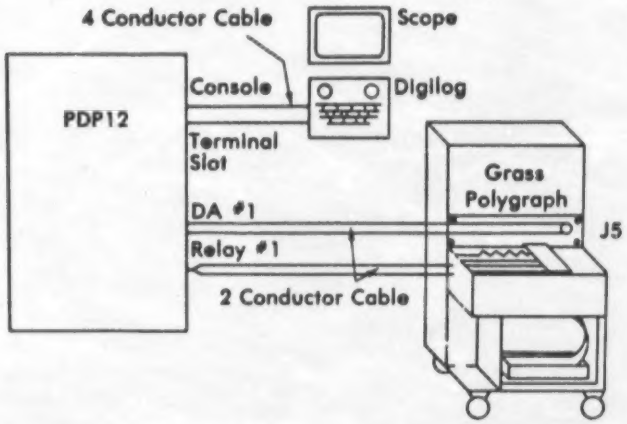
Simulation should begin. Read and follow instructions as they appear on the TV screen.

Listings of programs may be obtained by writing:

Dr. S. Katz
Department of Physiology
Medical University of South Carolina
171 Ashley Avenue
Charleston, SC 29403

LINC tape version of program is available for $20.00 or $10 plus a new tape.

Paper tape version is available at $10.00/copy.



APPENDIX 3

Alternative hardware necessary to run simulation*

Challenger II P (Ohio Scientific)**	
C2-4P 4K Microprocessor (8K Basic Included)	$ 598.00
CA7C A/D Converter	399.00
CM-3 16K Memory	498.00
TV Monitor	150.00
5V DC mini relay TTL compatible (available at most electronic stores)	10.00
Cassette Tape Recorder	60.00
	$1,715.00

*Program would have to be converted to BASIC code and assembly language. The program would then have to be keyed in. Once this was done the program could be off-loaded to cassette tape and the tape used to load the program at the users convenience.

For an additional cost for hardware a system could be obtained from the same company that would not require conversion to BASIC. This more powerful system uses floppy disks and is capable of utilizing FORTRAN, Cost: $4,600. An additional benefit would be the ability to develop programs as well as rapid storage and retrieval of software.

**Ohio Scientific
1333 South Chillicothe Road
Aurora, Ohio 44202

NOTE: There are several other manufacturers making microprocessors capable of performing the same task. Ohio Scientific is used only as an example of available hardware.

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A DIGITAL COMPUTER SIMULATION OF CARDIOVASCULAR AND RENAL PHYSIOLOGY

Charles S. Tidball

Originally published: *Physiologist* 22(1): 37-43, 1979

The other three articles* in this series have described physiological simulations which can be performed on a microprocessor, a minicomputer, and an analog computer. The simulated areas included, respectively, portions of cellular, cardiovascular, and respiratory physiology. In this article, interaction with a more ambitious simulation dealing with both cardiovascular and renal physiology at the same time, will be described. It was developed on a medium scale computer and is intended for larger machines which are generally accessed under time-sharing operating systems enabling many users to interact with various programs and data bases simultaneously. Unlike the other items in the series, cost information on current equipment or new equipment is not presented because it is assumed that physiological simulation alone would be an insufficient basis for acquiring such an advance computer resource. Nevertheless, technical information has been included in the Appendix to enable the reader, or a computer knowledgeable colleague, to determine if locally available equipment will be able to support physiological simulation at this level of sophistication. In the absence of an adequate institutional computer resource, it is also possible to utilize commercial service bureaus or educational networks. However neither of these approaches are likely to be economical in the long run, therefore they should probably be restricted to trial use or other relatively short-term applications such as a workshop or a conference.

The physiological model MACPEE (1) is one of a family of digital computer simulations developed by C.J. Dickinson and colleagues as the result of collaborative efforts extending continuously since 1970, between McMaster University Medical School in Hamilton, Ontario, Canada; University College Hospital Medical School, London, England; and (more recently) St. Bartholomew's Hospital Medical College, London, England.

The first program developed by this group was a computer model of the heart and peripheral circulation called MACMAN (2, 3). This program is a relatively simple simulation of cardiovasular physiology, not unlike the one described by Katz *et al* in a preceding paper (4); it has been in use for sufficient time that it no longer requires frequent revision. Under the name Cardiac Simulation, it is available from a computer at The Massachusetts General Hospital (5) which is connected to a national network thus obviating long distance telephone charges. The latter can be accessed through the auspices of the Health Education Network, Inc., a user-directed, not-for-profit corporation supporting inexpensive distribution of interactive, computer-driven, educational materials in the health sciences (6).

The second member of the MAC family of physiological models is a simulation of pulmonary physiology called MACPUF (7). This is a somewhat more complex model which has also been available long enough to be in a stable configuration. The physiology underlying the assumptions used to develop the equations is well documented in a recent monograph by Dickinson (8). The latter contains a complete listing of the program which is written in the computer language FORTRAN.

Rationale for Selection

There are advantages in describing one or the other of the original models, however there are also some reasons which favor the selection of MACPEE. First that simulation incorporates the essential features of MACMAN plus a good deal more:

1. kidneys capable of excreting water, urea, sodium, and potassium;
2. a gastro-intestinal tract which absorbs water, protein, sodium, and potassium;
3. a thirst mechansim governing water control in accordance with the body needs; and
4. an endocrine system with individual control of the secretion rates of vasopressin (ADH). aldosterone and angiotensin.

Thus MACPEE represents an ambitious attempt to undertake physiological simulation under circumstances involving interplay among a number of different organ systems.

Second, the simulation is still under active development. As the authors state:

> Whereas we belive that MACPUF is in most essentials physiologically and clinically accurate, we recognize that this is not (yet) the case with MACPEE. In particular, quantification of stress relaxation of veins, circulation and interstitial space compliance, autoregulatory behavior of systemic circulation, renal blood flow, and GFR, and renin-angiotensin-aldosterone interactions are not well enogh understood to allow an entirely accurate simulation. We hope that users' comments and criticisms will help us to improve the model (9).

Third, the model has been available for more than five years and has had considerable student and professional feedback. And fourth, the model incorporates significant flexibilities in format presentation which are not usually found in simpler simulations. For all these reasons, MACPEE seemed a likely candidate to round out the state-of-the-art of physiological simulation which we are trying to present in these two issues of *The Physiology Teacher*. Because description of only one simulation program is intended in this article, readers interested in other models and a programming aid developed by this group are referred to the Appendix for additional details.

*Articles orginally published in "An Expression of the State of the Art with Regard to Physiological Simulation" have been reprinted here as chapters 8, 10, 5 and 7.

DESCRIPTION OF MACPEE

A General View of the Model

The description of MACPEE contained herein is based on version 78.2 dated July 28, 1978 as noted in the first line of the program. In Figure 1, taken from the MACPEE User Manual (10), is shown a diagram with the essential elements of the model. The model contains 25 changeable parameters (see Table 1) and 95 computed variables (see Table 2). For convenience these are called "factors" by the program and are referred to by unique numbers in the range from 1 to 120. Perusal of these tables is the best way to appreciate the scope of the model. The presentation of variables in Table 2 is by physiological system. It is also interesting to note a few variables, such as 'Urine output in previous iteration interval'; these are not physiological values in the customary sense but represent intermediate quantities necessary for successful operation of the computer model. Similarly, a number of arbitrary indices, such as 'Average sympathetic nervous activity' are also defined to permit the model to have a broader latitude of operation.

Format of Computer Output

MACPEE does not require a unique terminal since it does not utilize any special graphic capabilities. The output can be displayed either on a cathode ray tube device using conventional video technology, or the alphabetic and numeric characters can be printed by any hard-copy terminal which is compatible with the computer system. In either case, typing skills are not needed since responses to MACPEE consist entirely of numbers.

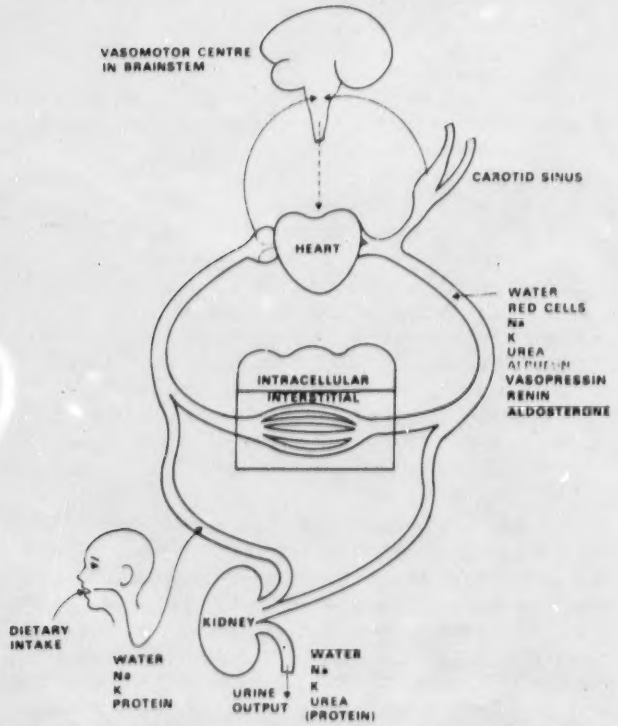

Fig. 1. Diagramatic representaton of the MACPEE physiological model with particular reference to input/output considerations and available regulatory features.

TABLE 1

LIST OF CHANGEABLE PARAMETERS (FACTORS)IN MACPEE*

Factor #	Title	Units	Approximate Normal Value
1	Dietary sodium intake	mM/day	140
2	Dietary protein intake	g/day	90
3	Potassium gain or loss	mM/day	0
4	Cardiac contractility	% of normal	100
5	Whole body arterial resistance	% of normal	100
6	Renal arterial resistance	mm Hg	0
7	Whole body venous resistance	% of normal	100
8	Renal glomerular function	% of normal	100
9	Renal tubular sodium reabsorption	% of normal	100
10	Vasopressin function	% of normal	100
11	Renal protein loss	g/day	0.1
12	Aldosterone function	% of normal	100
13	Intrathoracic pressure	mm Hg	-2
14	Cardiac filling pressure	mm Hg	8
15	Total body exchangeable sodium	mM	3,000
16	Total body exchangeable potassium	mM	3,500
17	Total body urea	mg	1,500
18	Total body albumin	g	120
19	Total body red cell mass	ml	2,300
20	Lean tissue mass**	Kg	30
21	Total body water	1	38
22	Venous system capacitance***	ml/mm Hg (14)	170
23	Baroreceptor sensitivity	mm Hg	0
24	Allowable maximum fluid intake	ml/day	10,000
25	Extra fluid intake	ml/6 hours	0

* The first 8 of these factors and their current values are printed in abbreviated form in the standard MACPEE output (see Figure 2).

** The body weight is the sum of factors 20 and 21.

*** The volume which this capacitance determines is added to the obligatory volume of 3000 ml that is necessary to fill the circulatory system at atmospheric pressure.

TABLE 2

PARTIAL LIST OF COMPUTED VARIABLES IN MACPEE*

General Area	Name (Units)
Hemdynamics	Cardiac Output (liters/min)
	Effective Cardiac Contractility (liters/min per mm Hg Effective Filling Pressure)
	Heart Rate (beats/min)
	Systemic Arterial Blood Pressure (mm Hg)
	Average Capillary Pressure (mm Hg)
	Average Tissue Pressure (mm Hg)
	Cardiac Filling Pressure (mm Hg)
	Effective Venous Capacitance (ml/mm Hg)
	Systemic Arterial Resistance (mm Hg/(L/min))
	Systemic Venous Resistance (mm Hg/(L/min))
Fluid Intake	(ml/day)
	Intake in Previous Iteration Interval (ml)
Kidneys	Renal Blood Flow (ml/min)
	Glomerular Filtration Rate (ml/min)
	Glomerular Filtration Pressure (mm Hg)
	Pre-glomerual Vascular Resistance (ml/min per mm Hg Pressure Difference)
	Renal Interstitial Fluid Pressure (mm Hg)
Urine	Output/Day (ml)
	Output in Previous Iteration Interval (ml)
	Sodium Output/Day (mM)
	Sodium Output in Previous Iteration Interval (mM)
	Potassium Output/Day (mM)
	Potassium Output in Previous Iteration Interval (mM)
	Urea Output/Day (mM)
	Urea Output in Previous Iteration (mM)
	Albumin Output/Day (g)

Blood	Volume (ml)
	Hemoglobin Concentration (g/100 ml)
	Hematocrit (%)
	Plasma Volume (ml)
	Plasma Osmolality (mOsm/kg)
	Plasma Sodium Concentraton (mM/L)
	Plasma Potassium Concentration (mM/L)
	Plasma Urea Concentration (mM/L)
	Blood Albumin Concentration (g/100 ml)
Cells	Intracellular Water (ml)
	Intracellular Sodium Concentration (mM/L)
	Total Intracellular Sodium (mM)
	Intracellular Potassium Concentration (mM/L)
	Total Intracellular Potassium (mM)
	Interstitial Fluid Volume (ml)
	Total Extracellular Fluid (ml)
Whole Body	Weight (kg)
	Autoregulation (Arbitrary Index)
Hormones	Renin (Plasma Renin Activity)
	Vasopressin (Arbitrary Index)
	Aldosterone (nanag/100 ml)
Miscellaneous	Average Sympathetic Nervous Activity (Arbitrary Index

As can be seen in Figure 2, the material delivered by the computer occurs in several portions. Initially there are some queries relating to: a) obtaining a brief description of the program (not requested in the run shown) and to b) selecting the units to be used (grams and milligrams were requested). Then there is a chart which indicates the time in days and hours. For each time entry there are corresponding data for cardiac rate (pulse) as well as diastolic and systolic blood pressure. These values are ordinarily presented at six hour intervals. The user can, however select other time spans. This is followed by a tabulation of laboratory data for the simulated patient based on the preceding 24 hour period, and by a listing of the first eight of the changeable parameters with their current values. (The latter feature is deleted automatically after several data presentations on the same subject.) Occasionally, simulated comments from the patient or the nursing staff are appended to the bottom of the output. Finally, there is the request from the computer to indicate what action is desired next. This is a standard message which occurs at the end of each major action by the program, therefore its various options have been detailed in Table 3.

```
--MACPEE--VERSION 78.2--28 JULY 1978--
TO PROCEED TYP 1 THEN PRESS 'RETURN' KEY,
TO GET BRIEF DESCRIPTION TYPE 2 AND THEN 'RET'
?
1
IF ANYTHING GOES WRONG NOTE WHAT YOU DID AND IN-
FORM YOUR TUTOR. A PRIZE OF $1 WILL BE GIVEN TO
ANYONE CONVINCINGLY SHOWING IMPOSSIBLE
BEHAVIOUR OF THE MODEL IN A POSSIBLE CLINICAL
SITUATION. ANY TIME YOU CAN'T UNDERSTAND SOME
QUESTION OR INSTRUCTION TYPE 'Q' (QUERY) AND PRESS
THE 'ESCAPE' KEY
OK, WE'RE OFF . . .
TO USE G. AND MG. TYPE 1, FOR S.I. UNITS TYPE 2
?
1
SYMBOLS XXXXX = SYST. + DIAST. B.P. *** = HEART RATE
TIME 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
DAY HRS. . . . . .
0. 600.                    XX*XXXXX
FINAL VALUES RECORDED (SINCE 6 A.M.) WERE...
FLUID INTAKE = 1796. ML   URINE UREA = 24.5 G
URINE OUTPUT = 1351.        SODIUM = 136. MMOL
                          POTASSIUM = 66.
PLASMA(NA) = 142.(K) = 4.1MMOL/L UREA = 23.6 MG/DL
                          (DIV.BY 2 FOR BUN)
                          PCV = 48. PERCENT
HAEMOGLOBIN = 15.7 G/DL
PLASMA ALB. = 4.1 G/DL 24 HR UR.PROT. = 0.1 G
  BODY WEIGHT = 70.4 KG
B.P. 99/59 (MEAN = 73.) R.ATRIAL PRESS. = 2. MM HG
  HEART RATE = 69.
1.DIET NA = 140. 2.PROT. = 80. 3.+/- K = 0.
  4.CARD.FUNCT. = 100.:
5.ART.R. = 100. 6.R.ART.P.D. = 0.MM 7.VEN.R. = 100.
  8.GLOM.FUNC. = 100.:
DO YOU WANT TO..1.CHANGE, 2.CONTINUE, 3.RESTART,
  4.INSPECT, 5.STOP
?
2
TIME 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
DAY HRS. . . . . .
  0.1200.          *XXXXXXXXX
  0.1800.          *XXXXXXXXX
  0.2400.          X*XXXXXXX
  1. 600.          X*XXXXXXX
FINAL VALUES RECORDED (SINCE 6 A.M.) WERE...
FLUID INTAKE = 1792. ML   URINE UREA = 23.5 G
URINE OUTPUT = 1158.        SODIUM = 100. MMOL
                          POTASSIUM = 66.
PLASMA(NA) = 142.(K) = 4.1 MMOL/L UREA = 25.7 MG/DL
                          (DIV.By 2 FOR BUN)
HAEMOGLOBIN = 15.5 G/DL   PCV = 47. PERCENT
PLASMA ALB. = 4.0 G/DL 24 HR UR.PROT. = 0.1 G
  BODY WEIGHT = 70.6 KG
B.P. 105/63 (MEAN = 78.) R.ATRIAL PRESS. = 2. MM HG
  HEART RATE = 68.
```

Fig. 2. Typical run of MACPEE indicating blood pressure/pulse chart, laboratory data, and settings for the first 8 factors on the factor list. Underlined values represent user input.

TABLE 3
EXPLANATION OF OPTIONS IN STANDARD MESSAGE

Option #	Name	Action
1	CHANGE	permits the user to alter any of the 25 changeable parameters listed in Table 1.
2	CONTINUE	causes the computer to provide an additional 24 hours worth of subject data.
3	RESTART	cancels the current subject and causes the computer to begin the presentation of a new subject.
4	INSPECT	causes the computer to print a complete table of computed results.
5	STOP	returns the user to the monitor level of the computer system being used.

Options for Making Interventions

In Figure 3, a sequence is depicted in which the CHANGE option was utilized to reset the value of Factor 8 (Renal Glomerular Function) from 100% of normal to 20% of normal. Then the CONTINUE option was requested twice, in a single command (2/2), to obtain two consecutive 24 hour presentations which detail the consequences of that particular alteration in renal glomerular function. Note that the urine volume decreases for the first 24 hour period but then returns toward normal, as one would expect, if the fluid intake continues at approximately 1800ml/day. By contrast, the plasma urea concentration approximately doubles over the first 24 hour period and continues to increase on the second day but at a slower rate of rise. Although the original decrease in renal glomerular function imposed on the simulated patient is a more abrupt change than one would expect under ordinary clinical circumstances, the alterations in function produced by the model represent reasonable approximations of what would occur in a human patient under such conditions.

It should also be pointed out that other possibilities exist with regard to the CHANGE option. As shown in Figure 3, requesting a change calls up a new query in which CHANGE VALUES is only the first among a number of choices. The FLUID (+/-) choice enables one to determine the intake of parenteral and oral fluids. Not only is it possible to select any of eleven standard fluids which are customarily infused intravenously, but one can also instruct the nursing staff either to restrict or to encourage a specified extent of oral fluids. The fluid therapy "orders" can be modified or cancelled after each iteration of the model. The remaining choices offered in the CHANGE option are described in the following section.

```
DO YOU WANT TO..1.CHANGE, 2.CONTINUE, 3.RESTART,
  4.INSPECT, 5.STOP
?
1
1.CHANGE VOLUES, 2.FLUIDS(+/-), 3.STORE/BKTRK,
  4.RUN CHANGE, 5.PRESETS
?
1
TYPE NUMBER OF FACTORS (1-25) TO CHANGE
?
8
FACTOR 8 (CURRENT VALUE=100.0), SPECIFY NEW VALUE
?
20
FACTOR 8= 20.0 (PREVIOUSLY= 100.0)
DO YOU WANT TO..1.CHANGE, 2.CONTINUE, 3.RESTART,
  4.INSPECT, 5. STOP
?
2/2
TIME 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
DAYS HRS. . . . . .
  0.1200.          *XXXXXXXXXX
  0.1800.          *XXXXXXXXX
  1.2400.          *XXXXXXXX
  1. 600.          *XXXXXXXX
FINAL VALUES RECORDED (SINCE 6 A.M.) WERE...
FLUID INTAKE=  1734. ML    URINE UREA=   8.4 G
URINE OUTPUT=   607.         SODIUM=    85.MMOL
                           POTASSIUM=    16.
PLASMA(NA)=141.(K)=4.6MMOL/L  UREA=    60.3 MG/DL
                          (DIV.BY 2 FOR  BUN)
HAEMOGLOBIN=15.2 G/DL          PCV=    46. PERCENT
PLASMA ALB.=3.9 G/DL 24 HR UR.PROT.=0.0G
  BODY WEIGHT= 71.1 KG
B.P. 106/63 (MEAN=78.) R.ATRIAL PRESS.= 2. MM HG
  HEART RATE= 67.
TIME 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
DAY HRS. . . . . .
  1.1200.          *XXXXXXXXXX
  1.1800.          *XXXXXXXXX
  2.2400.          *XXXXXXXX
  2. 600.          *XXXXXXXX
FINAL VALUES RECORDED (SINCE 6. A.M.) WERE...
FLUID INTAKE=  1672.ML     URINE UREA=   17.3 G
URINE OUTPUT=  1223.         SODIUM=    135.MMOL
                           POTASSIUM=    60.
PLASMA(NA)=141.(K)=4.8 MMOL/L  UREA=    76.2
                                        MG/DL
                          (DIV. BY 2 FOR  BUN)
HAEMOGLOBIN=15.1 G/DL          PCV=    46. PERCENT.
PLASMA ALB.= 3.9 G/DL 24 HR UR.PROT.= 0.0G
  BODY WEIGHT= 71.1 KG
B.P. 106/63 (MEAN= 78.) R.ATRIAL PRESS.= 2. MM HG
  HEART RATE= 66.
```

Fig. 3. Run of MACPEE in which CHANGE option is utilized to decrease Factor #8, Renal Glomerular Function, from 100% of normal to 20% of normal. The simulated patient is then followed for two 24 hour periods.

Now let us return to the remainder of the options in the standard message as shown in Table 3. RESTART and STOP seem reasonably obvious. In Figure 4 are depicted the results of requesting the INSPECT option. As is indicated in the MACPEE User Manual, "Nearly everything you could possibly want to know is displayed". This option can be selected each time the computer requests what action is desired next.

Advanced Capabilities of MACPEE

It is beyond the scope of this presentation to provide details of the ways in which MACPEE can be altered for special categories of users. However, because program flexibility is often unavailable in physiological simulations, some of these capabilities deserve recognition. For example, it is possible to store the present status of a particular subject and have the computer return to that status upon request. This is accomplished by using the STORE/BKTRK choice in the second query which comes up after requesting the CHANGE option. It is also possible to change the display by suppressing portions of the standard output or by deleting the graph and/or the laboratory data. Similarly, the number of hours for the next run and the number of minutes in the iteration interval may be altered. These features operate from the RUN CHANGE choice. Finally, there are additional flexibilities which would be of value to those who might like to use the model for research purposes.

MAXIMIZING THE STUDENT EXPERIENCE

It should be emphasized that a computer-driven physiological simulation differs frim a reading assignment, a traditional audio-

```
DO YOU WANT TO..1.CHANGE, 2.CONTINUE, 3.RESTART, 4.INSPECT, 5.STOP
?
4
```

	WATER	SODIUM			POTASSIUM		UREA	OSM	ALBUM.
	ML.	MMOL	MMOL/L	MMOL	MMOL/L	G	MG/DL	MOSM/L	G G/DL
WHOLE BODY	42185.	2689.		3140.	(TOT.EXCH.)				
UNSPECIFIED	10233.	538.		201.					
CELLS	18006.	168.	9.	2881.	160.	11.)	26.	278.	
E.C.F.	13946.	1988.	142.	58.	4.1	)			
INT.FLUID	11439.		142.		4.1		26.	278.	0.8
BLOOD	4725.								
PLASMA	2500.		142.		4.1		26.	278.	101. 4.0
RED CELLS	2218.						26.		
CUM.INTAKE	1792.	140		63.	(	24.)			
CUM.URINE	1158.	100.	86.	66.	57.	23.	2028.	644.	0.1
(SINCE 6 A.M.)					(FOR BUN DIVIDE UREA BY 2)				

	ART.	VEN.	CAP.	GLOM.	INT.	RENAL	INT.FL.	
PRESSURES	105/63	2.	13.	50.	13.		-6.	HB = 15.5 G PCV = 47.
MM HG	(77.6)							
FLOWS - L OR ML/MIN	4.8			129. (GFR)		874.		HEART RATE = 68./MIN
RESISTANCES MMHG/L/MIN	13.8	2.4		31. (PRE)		87.		BODY WEIGHT = 70.6 KG
				55. (POST)				

Fig. 4. Example of INSPECT option format. This feature displays most of the variables used by MACPEE.

visual presentation, or even a module utilizing computer assisted instruction. It cannot be successful if "thrown" at the student without adequate preparation. At this institution we have, for more than five years, incorporated a required computer session as part of our laboratory teaching to first year medical and graduate students (11). These experiences have a limited set of learning objectives in part because of the lack of prior exposure to computational devices as well as differences in motivation to become involved at the computer terminal.

In essence, in order to gain maximum utility from a computerized physiological model, it is necessary to acquire three somewhat different sets of skills. The first of these sets is to develop sufficient familiarity with computer systems so that learning the following relatively simple but critical maneuvers does not inhibit further involvement with Computer Systems: a) connecting the terminal to the appropriate computer mainframe, b) satisfying the computer's "login" requirements, c) creating the necessary computer language environment, d) causing a copy of desired program to be transferred from mass storage to a user memory partition, e) beginning execution of the program, f) discontinuing interaction with the program, and g) making a legal disconnect from the system. For many educational computers a number of the skills enumerated above may be accomplished automatically by the computer. However such "convenience" at one stage of the student's exposure exacts a price when that student moves on to another computer system. It may not be quite as cordial to the user and, inevitably, has an entirely different set of conventions for these critical maneuvers.

The second set of skills involves understanding what is meant by a simulation. In our experience this has represented at least as difficult a challenge as mastering the first set of skills. Unfortunately, in spite of the fact that some of our students have previous exposure to computer technology, the concept of simulation is rarely taught. In order to introduce simulation principles, we found it highly successful in our laboratory sessions to use a simple simulation of a rocket ship attempting a soft landing on the moon. The problem posed to the student was not merely making a safe landing once, but discovering the key factors which make it possible to land safely every time. Under the conditions of the particular simulation we use, it is very difficult to land the craft successfully by trial and error; however when the principles are understood, it becomes trivial to land the craft perfectly at every attempt. This experience was perceived by the students as a legitimate exercise in developing problem solving skills using a simulation as a facilitator. It improved the performance in the more substantive portion of the laboratory exercise.

Finally, the third set of skills requires the integration of physiological principles into a human, or patient oriented, frame of reference. We generally teach physiology by organ system and perforce take up processes one at a time. The task of integrating these into a functioning whole is often left to the student with little or no guidance as to how this process is to be accomplished. A physiological simulation program is an ideal medium to support this important integrative activity. The MACPEE User Manual contains ten practice problems which have considerable clinical relevance, but even these must be placed in the local instructional context before the students will make the desired associations. However, it must be acknowledged, integration does *not* take place in the absence of adequate instructor support: there is no substitute for the involved presence of faculty members while the students interact at the terminal with the physiological simulation models.

The model is almost infinitely versatile; and being a true simulation, it can accommodate any sequence of alterations which the user desires to request. Unfortunately, as discussed elsewhere (2), the model does not warn the user when it embarks on ranges of values which are no longer reasonable. That, however, is easier to point out than to correct; many variables are involved and the many pathological conditions which can be simulated cause a great variety of alterations in each variable. Nevertheless, to enhance the utility of this model for teaching purposes, it would be desirable to incorporate some built-in warnings to indicate when the model is entering areas where the results may not be entirely plausible.

A second criticism is the lack of a description detailing the overall design of the model from the physiological point of view. Documentation, when it does become available, should include assumptions that had to be made as well as values that had to be assigned arbitrarily, in order to render the model functional. It is recognized that this sort of documentation is available for MACPUF (8), and it may be that MACPEE is not yet sufficiently mature to permit developing and publishing the overall design of the model. Nevertheless a documented model can be incorporated into a teaching program with greater ease and confidence.

Finally, many features not only in the practice of science and medicine but also in all aspects of this complex 20th century existence, are relying more and more on computer technology for essential support. Thus it is desirable to have a variety of computer-based learning experiences available to the student and the practitioner who feel a need for the better understanding of physiology which a computerized model can convey. MACPEE is an excellent vehicle for this purpose and is recommended to all institutions wishing to expand their capabilities in the area of physiological simulation.

APPENDIX

The MAC Family of Physiological Models

MACMAN:	Computer Model of Heart and Peripheral Circulation*
MACPUF:	Computer Model of Lungs and Blood Gas Exchange*
MACPEE:	Computer Model of Kidneys and Body Fluids*
MACDOPE:	A Computer-based Model for Training in Pharmacokinetics and Techniques of Prescribing*
MACBABE:	Computer Model of Lungs and Blood Gas Exchange, relevant to Newborn and Premature Infants
MACDIVE:	Computer Model of Blood/Gas Exchange, Gas Transport and Storage, applicable to Decompression and Compressed Air Work
MACAID:	McMaster Computer-aided Instructional Driver

* Introductory lecture demonstrating the model is available in three different videotape formats at price ranging from $100-160. For more information contact:

Mrs. Sheila D. Tibbats
Co-ordinator, Learning Resources, Room 1 G 8
McMaster University Medical Centre
1200 Main Street West,
Hamilton, Ontario, CANADA L8S 4J9

Technical Information for Running a MAC Model.

MACPEE (and the other MAC physiological models) are coded in the computer language FORTRAN. Care has been taken to avoid, as far as possible, machine dependent features so that the program can be adapted to other computers with a minimum of inconvenience. At McMaster University the model is implemented on a Hewlett-Packard 3000 computer but the author accesses the programs from a Digital Equipment Corporation PDP-10 computer located at the National Institutes of Health in nearby Bethesda, MD. Virtually any computer which has an *Interactive* FORTRAN capability and at least 56 thousand bytes of memory should be able to run the program. The program is available from McMaster University or from St. Bartholomew's Hospital at a nominal fee of $250. An additional charge of $100 is made for the listing of the code. Updates are distributed at $50 each. Various tape formats can be requested.

For more information contact:

United Kingdom and Europe	All other countries
Dr. D. Ingram	Dr. K. Ahmed
Department of Medicine	Computation Services Unit
St. Bartholomew's Hospital Medical College	McMaster University Medical Centre
West Smithfield	Hamilton
London EC1A 7BE	Ontario L8S 4J9
ENGLAND	CANADA

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SECTION FIVE - SOME CAUTIONS WITH REGARD TO PHYSIOLOGICAL SIMULATION

Chapter Twelve

PHYSIOLOGICAL SIMULATION: AN ASSESSMENT OF ITS ADVANTAGES AS WELL AS ITS LIMITATIONS

Roy A. Standing and Charles S. Tidball

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As computing facilities become accessible to more people and at lower costs, it is becoming more attractive to use computer simulations in the teaching of physiology. In fact, as the technology advances some use of computer simulations for training may become mandatory (15). This presentation is made in three parts: the first section reviews some of the advantages to be gained by the use of computer simulations in support of conventional educational methods. The second topic discusses the evaluation of simulation programs for teaching purposes. The third portion of the paper deals with some limitations of the simulation approach.

ADVANTAGES OF USING COMPUTER SIMULATIONS

The advantages to be gained in the use of computer simulations relate to a variety of activities as indicated below.

Faculty Time

Traditional educational methods require faculty and staff to teach and train students in all the topics covered in a course, from those which are conceptually simple but require practice to master, to those which are conceptually complex and require extensive thought and understanding. By designing simulations to take over the straight-forward tasks and to assist in the understanding of elements of more complex tasks, the faculty can recover time. This time could be used to prepare and lecture on more complex issues or to devote to research which typically includes student involvement.

The potential for this recovery of time has been amply demonstrated. Alpert and Bitzer (2) reported, in 1970, on a program written to test the feasibility of replacing some lecture time in a medical science course with program interaction time. Students who used the computer programs needed only one third to one half as many lecture hours as those students who relied solely on lectures. Attia et. al. (3) tested a case-simulation program for teaching cardiopulmonary resuscitation with first month anesthesiology residents at The Massachusetts General Hospital. Residents using the program learned significantly more than their classmates who only had access to textbooks and tutors.

Laboratories

Laboratory instruction is typically intended to accomplish at least two purposes: a) to develop particular skills in the students, and b) to present problem-solving situations which the student may later encounter and thus provide solutions (or guidelines) for those situations. While some activities must be dealt with in a laboratory, e.g. dissection and instrumentation, many can be dealt with using computer simulations. When evaluation of results is of paramount importance, the use of computer assisted instruction (CAI) can be invaluable. Instead of spending time performing tests (which may require elaborate equipment and time consuming preparations) and writing conjectures on their results, students can request the necessary tests and then apply their conjectures to a model of the system under consideration, thus maximizing the cognitive aspects of the exercise.

Student Involvement

At least three motivational factors affect student learning: a) the nature of the teaching environment, including the amount of individual attention; b) the presence of opportunities to test the newly-learned material in a life-like situation; and c) the opportunity to explore a broad range of related topics. As argued persuasively by Hoffer et. al. (13), medical students are required both to amass knowledge and to develop competance in the application of that knowledge. Only the former is taught in a well-structured fashion; the latter is taught by exposure and experience in a clinical setting which is limited by the realities of life. There is no control over the selection of patients, the stage of their illness, or their time of arrival at a hospital or clinic. Further the mix is often atypical of what is likely to be found in private general practice, and worse – for teaching purposes – either the situations are emergencies which leave little room to discuss choice of treatment, or the maladies are so complicated that the patient's care cannot be entrusted to an inexperienced student. Thus, supervised practice in a clinical setting is necessary but severely limited. Computer simulations which place the student in complete control of a patient, and which can present rare clinical diseases at the touch of a button, are a helpful solution to much of this problem. These solutions extend to computer-controlled mannequins such as Gordon's (9, 10), or Abrahamson's (SIM-I) at the University of Southern California School of Medicine (1, 5). While medical students may present a somewhat extreme example, students preparing for any form of laboratory-associated career can benefit from such computer-based learning opportunities.

New Topics

Many topics can be taught via simulation programming which could not be taught otherwise. Using medical students as an example again, it is obvious that a patient with an acute illness cannot be placed in the care of an inexperienced medical student. Conversely, a student can be permitted considerable latitude in exploring the dynamic parameters of a disease in a simulated patient. For example, a student could deliberately withold treatment in such a simulation to observe the natural course of a disease

process. That type of experience might be of benefit in later practice as a guide for assessing the progression of a patient's disease and selecting among therapy alternatives. Additionally, the student could gain valuable experience with procedures requiring elaborate or expensive equipment without incurring any actual cost or subjecting a patient to possible training errors. Thus, a simulation can provide experiences that would not be ethical in a real-life situation or might only occur infrequently in practice.

EVALUATING COMPUTER SIMULATIONS

Teaching Level

Whether a simulation demonstrates physiology at an appropriate level for a student and whether it provides a useful learning experience are crucial concerns which are often difficult to resolve. With respect to the first concern, the simulation must not overwhelm the student with physiological detail yet it must represent physiology faithfully. (This concern is dealt with more fully in subsequent sections.) The second concern is essentially a methodological one and as such does not have a single clear-cut answer. In order to provide a useful learning experience, several factors must be present; motivation to participate in the experience, challenge to make the participation worth the effort, review to consolidate present knowledge, and new material to either increase knowledge or to extend understanding by demonstration new relationships between known material. The balancing of these factors is subjective however some basic requirements do hold. Simply submitting prescribed data to a simulation is not likely to stimulate student interest unless some frame of reference is available to enhance the feeling of involvement. Interactive simulations provide more motivation because the student is able to make a series of inputs to the simulation, follow a sequence of events, and attempt to achieve a desired outcome. Management to achieve a final outcome or exploration of a particular scenario can provide an appropriate challenge. The involvement of using knowledge as well as acquiring and determining the need for new information is obvious in such contexts. Those programs which provide a seemingly new experience each time they are engaged contribute more to motivation than those which are less versatile.

Range of Response

Physiology is customarily defined as the science dealing with the normal vital processes of human beings and animals. For our purposes it will be useful to make distinctions between the terms 'normal' physiology, 'abnormal' physiology, and patho-physiology. Normal physiology will be used to describe physiochemical processes operating within their homeostatic limits, abnormal physiology will be concerned with processes which are operating outside their homeostatic limits in the absence of an identifiable pathological agent, and patho-physiology is the study of processes affected by the intervention of diseased or degenerative conditions.

The physiological interrelationships which exist in normal physiology may change dramatically in certain abnormal states. This is in part because physiological actions are generally controlled by a multiplicity of other interlocking physiological processes. Some processes exert a large absolute effect which provides a gross adjustment while others exert a small absolute effect which provides only fine-tuning. For example, pH balance is controlled by the renal, pulmonary, and blood buffer systems. While the blood buffer system has the smallest absolute effect it is adequate to control the blood pH under resting conditions. Following exertion, the capacity of the blood buffer system is exceeded and the pulmonary system is called upon to restore acid-base balance. For conditions which occur over a longer time period the renal system can provide more sustained adjustments.

It is insufficient to state that a particular relationship exists between a number of factors within a defined range if the model can operate beyond that range. The formulas which describe the relationships between factors must describe them accurately over the full range that the simulation operates, not simply a 'normal' range or a 'range of interest'.

The simulation should prevent itself from entering situations it is not equipped to handle. This requires each set of equations to check its input parameters. If any input is outside the permissible bounds, the simulation should reject the user input, print a message explaining the program's action, and restore the simulation to the condition it had before the unacceptable input was made.

Assumptions

When functioning in a research capacity it is permissible, if not desirable, for a physiologist to speculate in describing a physiological process. A trained researcher can construct a simulation reflecting a particular viewpoint about how some physiological process works and use it to test a hypothesis or to predict what to look for in laboratory experiments. In a teaching situation, however, such latitude can be dangerous. A naive student is often unable to distinguish an invalid result from a valid one. The background and perspective of experience is lacking, and the student is apt to accept everything as fact. The assumptions of a simulation must be as well documented as possible and should be clearly stated to the student.

Formulation of Equations

A crucial question is whether the simulation programming reflects physiological processes, or simply displays the results of certain specified circumstances. To examine this question adequately it is necessary to consider the structure of simulation programs. Simulation programs can be divided into three categories; pseudosimulations, empirical simulations, and physiological simulations.

Pseudosimulations use a question/answer format to branch from physiological state to physiological state. While such programs can be quite complex there is no actual mathematical simulation involved. The question/answer structure only allows the user to branch to specific sets of circumstances for which particular parameter values are available. While some minor modification is possible, the parameter values are not computed, rather pre-assigned values are employed. Examples of this type of simulation are Cardiopulmonary Resuscitation (12) available via the Health Education Network, Inc. (HEN) from The Massachusetts General Hospital and CASE (11) available via HEN from The Ohio State University.

Empirical simulations are based on an integrated set of mathematical equations which represent a non-physiological system. The values of the parameters of the simulation are determined at any given time by solving the set of simulation equations. The vast majority of equation-based simulations available today fall into this category, including many programs which purport to demonstrate real physiological systems. Examples of empirical simulations are MACMAN (8, 14, 16), MACPUF (7, 16), and MACPEE (6, 16) developed at MacMaster University in Ontario, Canada, and Cell Membrane, a simulation game which is used in the teaching program at The George Washington University Medical Center (16).

Physiological simulations differ from empirical simulations by faithfully representing real physiological systems in all their known detail. If the simulation is able to mimic the real system in every detail, then it is a true physiological simulation. Despite the vast amount of physiological knowledge available to the designers of simulations today, few physiological systems are fully understood and therefore there are few candidates for the designation true physiological simulation. Typically only portions of systems are fully understood and therefore simulations which limit themselves to those areas tend to be quite restricted in scope. An example of a physiological simulation is the Cargille/Dixon model of the human menstrual system (4). This model was developed by exploring the literature and restricting the formulation of equations to documented relationships as much as possible. Further, the documentation within the model states all assumptions and sources; as well as sources of conflicting data and viewpoints (see Figure I).

```
614 NOTE  ------------------------------------
615 NOTE
616 NOTE                          FSH
617 NOTE
618 NOTE  ------------------------------------
619 NOTE
620 NOTE
621 R    FSHPR.KL=18.2(100/(1+4.7*(HILL(.6*EBC.K,2.8)+.1*PBC.K)))
622 NOTE                          FSH PRODUCTION RATE (MIU/DAY)
623 NOTE*
624 NOTE* DEFINITION:
625 NOTE*   FSHPR IS THE NUMBER OF MIU OF FSH SECRETED BY THE
626 NOTE*   PITUITARY PER 24 HOURS, EXCLUSIVE OF THE FSH CONTRIBUTE
627 NOTE*   BY THE MIDCYCLE SURGE.
628 NOTE* ENGLISH TRANSLATION OF THE DYNAMO EQUATION:
629 NOTE*   THE FSH PRODUCTION RATE DURING THE NEXT INTERVAL IS EQUAL
630 NOTE*   TO 18.2 TIMES 100 DIVIDED BY 1 PLUS 4.7 TIMES THE QUANTITY
631 NOTE*   1.6 TIMES THE PRESENT ESTROGEN BLOOD CONCENTRATION AS IT
632 NOTE*   APPROACHES AN UPPER LIMIT OF 2.8 PLUS .1 TIMES THE
633 NOTE*   PRESENT PROGESTERONE BLOOD CONCENTRATION)
634 NOTE* DATA MODELLED:
635 NOTE*   1.  FSH PATTERN.
636 NOTE*       ROSS ET AL. REC PROGR HORMONE RES 26:1, 1970. FIG 9
637 NOTE* SUPPORTING EVIDENCE:
638 NOTE*   1.  FSH PATTERN.
639 NOTE*       FAIMAN ET AL.: J CLIN ENDOCR 27:1711, 1967.
640 NOTE*       MIDGLEY ET AL.: J CLIN ENDOCR 28: 1699, 1968.
641 NOTE*       MORI: J ENDOCRINOLOGY 42:55, 1968.
642 NOTE*   2.  INVERSE RELATIONSHIP OF E AND FSH.
643 NOTE*       VAITUKAITIS ET AL.: J CLIN ENDOCR 42:56, 1968.
644 NOTE*   3.  INVERSE RELATIONSHIP OF P AND FSH.
645 NOTE*       INSERT REF.
646 NOTE* CONTRARY EVIDENCE:
647 NOTE*   1.  FSH PATTERN.
648 NOTE*       SAXENA ET AL.: J CLIN ENDOCR 26:519, 1968.
649 NOTE*   2.  INVERSE RELATIONSHIP OF E AND FSH.
650 NOTE*       FSH RISE FOLLOWING E ON DAY 10 OF THE CYCLE NOTED
651 NOTE*       CARGILLE ET AL.: J CLIN ENDOCR 36:87, 1973.
652 NOTE* ASSUMPTIONS:
653 NOTE*   1.  FSHPR IS ONLY EFFECTED BY EBC AND PBC.
654 NOTE*   2.  CODE C. AT E LEVELS LESS THAN PROG, E IS 6X MORE EFF
655 NOTE*       THAN P IN SUPPRESSING FSH, NG FOR NG.
656 NOTE*   3.  CODE C. E AND P ARE ADDITIVE, NOT SYNERGISTIC, IN
657 NOTE*       SUPPRESSING FSH.
658 NOTE* LOCAL STRUCTURE - THIS ELEMENT IS EFFECTED BY:
659 NOTE*   EBC         (ESTROGEN BLOOD CONCENTRATION)
660 NOTE*   PBC         (PROGESTERONE BLOOD CONCENTRATION)
661 NOTE* LOCAL STRUCTURE - THIS ELEMENT EFFECTS:
662 NOTE*   FSHBC       (FSH BLOOD CONCENTRATION)
663 NOTE* COMMENT:
664 NOTE*   THE COEFFICIENT 18.2 EMPIRICALLY ADJUSTS THE RANGE OF FSH
665 NOTE*   LEVELS TO COINCIDE WITH THE NORMAL MEAN BLOOD LEVEL.
666 NOTE* ------------------------------------
```

Fig. 1 Portion of the Cargille/Dixon model of the human menstrual cycle. This is the program documentation for one of the follicle stimulating hormone (FSH) equations.

Since simulations have been shown to be an effective instructional media, and since current knowledge in many areas of physiology is insufficient to allow true physiological simulations to be written for them, it is practical to accept some empirical simulations. It is undesirable, however, to accept empirical simulations in those teaching settings where there is no opportunity to point out their limitations.

LIMITATIONS OF COMPUTER SIMULATIONS

Empirical 'Short-Cuts'

As we know them, the processes of physiology are quite complex. To simulate such complex processes using a digital computer requires a considerable investment of computer resources. These resources include central processing unit time, memory, and mass-storage. Briefly, this means that a complex simulation can be costly to run. This cost has typically been of prime importance in the development of simulations to the point that sometimes cost has been more important than accuracy (the reasons for this are not relevant to this article). The result of this situation has been for authors to attempt to group series of physiological processes into simple all-inclusive formulas. We call these formulas empirical approximations or simply, short-cuts. While these short-cuts have frequently been necessary to produce a functional simulation, the programs generally conceal this internal simplification or make no attempt to restrict the use of the simulation to those circumstances where the short-cuts appropriately represent the physiology they replace. Additionally, this approach ignores a primary teaching objective: to teach the student the process, not just the results of the process. Figure 2a provides an illustration of a stylized physiological pathway and Figure 2b shows how an empirical short-cut equation might represent it. Table 1a provides an example of an empirical short-cut equation actually observed in a program attempting to simulate renal physiology. The large number of 'ignored' parameters (Table 1b) makes it obvious that the relationship is acceptable only under a very restricted set of circumstances.

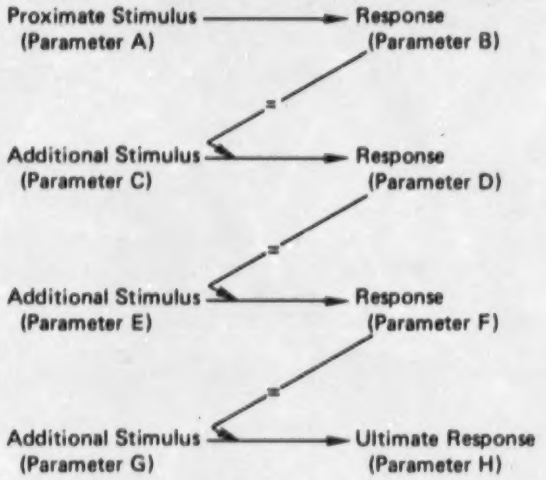

Fig. 2a. Stylized Physiological Pathway

Fig. 2b. Empirical Simulation of Physiological Process.

Note that the empirical simulation has simplified the physiological process by eliminating any modulating effects of the additional stimuli C, E, and G. In any circumstance where C, E, or G would significantly alter the ultimate response (H) the empirical simulation will give erroneous results.

Accepting the constraints of today's computer technology, it is inappropriate to suggest that all the factors involved in a physiological process must necessarily be present in a simulation, although this would be the ideal method. It is appropriate,

however, to require that the simulation document its departures from physiological processes and restrict its own operation to insure that it is always functioning within the range where it faithfully represents physiological processes. A systematic approach which could help the programmer decide when to eliminate physiological interactions with minimal effect on the accuracy of the simulation would be very helpful.

TABLE Ia. *'Short-cut' parameters used to determine urinary output of a substance.*

Parameters
Circulating blood level of excretable substance
Urine flow
Urine concentration of excretable substance

TABLE Ib. Some of the 'process-oriented' parameters that should be considered in a determination of urinary output.

Parameters
Circulating blood level of excretable substance
Arterial blood pressure
Renal blood flow
Glomerular filtration rate
Proximal tubular function
Counter current phenomena
Distal tubular function
Anti-diuretic hormone levels
Collecting duct exchanges
Urine flow
Urine concentration of excretable substance

Obviously the three parameters in Table 1a can only produce realistic answers under very restricted conditions for a restricted number of substances.

A Systematic Approach

In designing a simulation the first step must be to define the system to be simulated. For a physiological simulation this involves gathering a comprehensive collection of articles, monographs, books, etc. which reflect the current knowledge of the system. This collection is then employed to construct a diagrammatic chart indicating all documentable parameters and relationships. The relationships can be indicated by lines from one parameter to another with an arrow to indicate the direction of the effect in the relationship's normal range. A separate chart is constructed listing each relationship with notes, formulas, and bibliography.

Once constructed the diagrammatic chart can be used as the basis for subsequent development, the ideal simulation would use the diagrammatic chart without modification. To reduce the complexity of the chart it is examined for stimulus/response relationships. Where no other parameters mediate the relationship the stimulus/response parameters can be removed from the chart by connecting the input parameters of the stimulus side of the relationship to the output parameters of the response side of the relationship. This process can continue to the elimination of many stimulus/response relationships and while the simulation would become increasingly imprecise, the programmer would be aware of exactly where those imprecisions occur. Further, the simulation would always model the total defined system with all pathways closed, albeit simplified. Physiology can be divided into a number of logical subunits each of which can be treated in this fashion. By allowing free overlap and interchange between the subunits a number of simulations can be developed which can be connected to create simulations covering progressively larger areas of physiology. Such a series of simulations might be quite valuable if coordinated with the sequencing of systems taught in an accompanying course.

To be sure, this method entails a considerable amount of effort for each step. However, this process carries the benefit that every increment can be offered for peer review. Different groups could concentrate on different physiological systems, and changes could be implemented with minimal effort as new findings emerged. As with any research endeavor, future revisions would be suggested by gaps and contradictions in the literature. Simulations are not easy to develop; but until they are programmed to reflect adequately the complex interrelationships of real physiological systems, they will not demonstrate the subtleties of those systems or achieve their full potential as learning experiences.

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GLOSSARY

Charles S. Tidball

Note: the word computer is not in this Glossary except as a modifier; when used without qualification, computer is understood to refer to digital computer.

BASIC VOCABULARY

The terms listed below constitute a basic vocabulary (see Chapter 2). They are used so frequently in the Glossary definitions that it will be a distinct advantage to master this list of terms before attempting to use the Glossary.

access
analog
application program
binary
computer application
computer language
CPU
digital
execution
hardware
high-level language
instruction
mass storage
memory
microcomputer
operating system
peripheral device
programming
software
terminal

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It is a pleasure to acknowledge the contribution of Katherine C. Donovan to the development of this Glossary. Originally sought as a person without previous exposure to computer terminology, she cheefully learned enough computer interaction to master each definition and brought her extensive editorial skills to the task of rendering these definitions consistent with one another and as comprehensible as possible.

access process by which information contained either in **memory** or **mass storage** is made available to another sub-unit of a computer or, ultimately, to the user. Also refers to the ability of a computer **terminal** to communicate with a **remote computer.**

address number which identifies a location in the **memory** of a computer. Addresses are usually expressed either in **binary** notation or in a numerical equivalent of **binary.** Used as a verb to indicate **accessing** a particular **memory** location.

alphanumeric pertains to a character set that contains both letters and numerals, and usually other characters except those used in drawing pictures. Compare with **graphic.**

analog pertains to the use of continuously variable physical quantities such as electrical voltages, to represent numbers in a calculation. Compare with **digital.** Also an abbreviated form for **analog computer.**

analog computer type of computer that uses electrical voltages, or other continuously variable physical quantities, to represent numbers in a calculation. The process of measurement is used to arrive at solutions in an analog computer. By contrast, the process of counting is used to arrive at solutions in a **digital** computer.

analog-to-digital converter portion of a computer system which changes **analog** signals, usually electrical voltages, into discrete numbers capable of being processed by a **digital** computer. Electronic devices are also available to accomplish digital-to-analog conversions.

analysis category of **programming** which involves gathering information about **computer applications.** This process ordinarily precedes the **design** phase of the effort. Compare with **coding, testing,** and **implementation.**

ANSI acronym for American National Standards Institution, an organization which supports the development of standard versions for **computer languages.**

APL abbreviation for A Programming Language. APL is a general purpose, **high-level language** designed for **interactive** use which has powerful numerical and text-processing capabilities.

application program category of **software** which includes the **instructions** to a computer that solve a particular problem. Such problems are referred to as **computer applications.** Compare with **operating system** and **computer language.**

arithmetic processor board type of **special purpose board** which makes possible more rapid computer calculations by carrying out in **hardware** certain functions which would require multiple **instructions** if performed in **software.** The AM-9511 **integrated circuit** represents one of several approaches to the design of such an electronic **component board.**

ASCII acronym for American Standard Code for Information Interchange. ASCII refers to a convention for coding character sets in **binary** representation.

assembly language type of **computer language** consisting of abbreviations for **instructions** (mnemonics) and defined symbols. A computer **program** written in assembly language is used as **input** to another computer **program** known as an assembler which then generates a **machine language** version of the original computer **program.** Assembly language **programming** retains the full power and flexibility of the computer but it has two disadvantages: each different model of computer has a unique assembly language, and **programming** in this medium is more tedious to perform than is **programming** in a **high-level language.**

authoring aid special type of **application program** which facilitates the **programming** of **courseware** by enabling a content expert to **interact** with the computer and have the **coding** performed automatically.

BASIC acronym for Beginner's All-purpose Symbolic Instruction Code, a general purpose, **high-level language** designed for **interactive** use which is intended to be simple to learn. BASIC is widely available on a variety of computers especially **minicomputers** and **microcomputers.**

batch-processing method of maximizing the utilization of computers in which a series of jobs are put through the **CPU** in sequence. Typically, the user is not able to **interact** with the computer during the **execution** of the job and thus this method is used for large-scale, data processing. Compare with **timesharing.**

baud unit of transmission rate which is equal to **bits** per second. Characters can be sent to **hard-copy terminals** by the computer at speeds from 110 - 1200 baud which translates to 10 - 120 characters per second. **CRT terminals** can display text at higher transmission rates, typically up to 960 characters per second.

BCD abbreviation for Binary Coded Decimal, a method for representing conventional (decimal) numbers in a **binary** number system which contains only the digits 0 and 1.

binary number system which uses a base of 2 rather than a base of 10 as is used in the conventional (decimal) number system. Binary numbers consist entirely of 0's and 1's. It is customary to use other number systems to represent binary numbers. Compare with **octal** and **hexadecimal.**

bit smallest unit of data. This word, which is a contraction of **binary** digit, usually refers to a number which is represented either by a 0 or a 1. All the **memory** locations in a computer have **addresses** which are expressed in **binary** terms. Compare with **byte** and **computer word.**

bus portion of **motherboard** in which **component boards** are installed so that they can obtain **access** to multiple power and communications channels. Modern computers have a single bus, the so-called "unitized" bus, which provides **access** to **memory, controllers,** and **interfaces** for each **component board** plugged into a **slot** on the bus.

byte group of **bits** usually operated on as a unit. Since it customarily requires a byte consisting of 8 **bits** to define an **alphanumeric** character, the 8 **bit** byte has become a defacto standard. Computer **memory** and **mass storage** are measured in terms of bytes. The symbols **K** and **M** are used, respectively, to designate thousands and millions of bytes. Compare with **computer word.**

CAI abbreviation for Computer Assisted Instruction. General sense - all varieties of computer supported education (the more modern term is **CBE**). Specific sense - those varieties of computer supported education which are primarily tutorial in their interaction. Compare with **drill and practice, CMI,** and **simulation.**

card see **component board.**

cassette drive type of computer **mass storage** device which utilizes the audio cassette with its 1/8" magnetic tape as the storage medium. Information contained on magnetic tape is usually stored serially and not susceptible to rapid retrieval. Such units are frequently used on low-cost, **microcomputers** and **terminals.** Compare with **diskette drive.**

CBE abbreviation for Computer Based Education, a general term which encompases a variety of techniques used to provide computer support in instruction. These vary from **drill and practice** through **CMI** and **CAI** (specific sense), to **simulation.**

CBEM abbreviation for Computer Based Education Materials. See **courseware.**

central processing unit see **CPU.**

character see **alphanumeric, graphic.**

chip se **integrated circuit.**

CMI abbreviation for Computer Managed Instruction, those varieties of **CBE** which involve primarily testing in their interaction. Compare with **drill and practice, CAI** (specific sense), and **simulation.**

COBOL acronym for COmmon Business Oriented Language, a special purpose, **high-level language** designed for **batch-processing** which has the features required for large-scale data processing. COBOL is widely available on a variety of computers, especially **maxicomputers.**

coding category of **programming** which involves generating the **computer language** version of the solution to the **computer application** that emerged from **analysis** and **design.** Compare with **analysis, testing,** and **implementation.** Also used to refer to a means of preparing information for storage in a form which enhances subsequent processing. See **information representation.**

component board physical part on which electronic components are mounted. Component boards have "edge connectors" which make contact at the **slots** of the **bus** to communicate with power channels and information channels. Multiple component boards are mounted on a common multi-channel device known as a **bus.** There are various kinds of component boards such as **CPU, memory, interface, controller,** and **special purpose boards.**

computer application human endeavor which is susceptible to being automated by the use of computer technology. Also any technique for applying computer technology to the solution of a variety of information processing problems.

computer assisted instruction see **CAI.**

computer games amusement which has been **programmed** so that the computer performs the necessary calculations. The dividing line between computer games and education is not always discernible since playing computer games teaches one how to **interact** with a computer.

computer language category of **software** which includes collections of **instructions** used in **programming.** Such **instructions** are designed so they can easily be converted to **machine language** for subsequent processing by a computer. Computer languages are of two general types: **assembly languages** or **high-level languages.** Compare with **operating system** and **application program.**

computer literacy knowledge of computer science, more specifically the rudiments of how computers function and how human beings are able to **interact** with computers.

computer mainframe see **CPU.**

computer memory see **memory.**

computer model see **simulation.**

computer program see **program.**

computer-readable pertains to the storage of information or **programs** in such form that they can be re-entered into mass-storage automatically. The media which permit such re-entry include punched paper tape, punched cards, **magtape, diskettes,** and disks.

computer terminal see **terminal.**

computer word pertains to the number of **bits** used in the **registers** of a computer system. Since length of the computer word determines how many **memory** locations can be **addressed** in a single **instruction,** larger and faster computers tend to have longer computer words.

configuration used to designate the type and number of such **hardware** components as **CPU's, memory, mass storage, line printers,** and other **peripheral devices.**

console arrangement of indicators and controls at the **CPU** which enable manual operation of the computer.

control unit component of computer central processing unit **(CPU)** which determines what is the next action to be taken automatically by the computer. Compare with **register** and **memory.**

controller variety of **component board** in a computer system which is responsible for high-speed communication between **memory** and **mass storage** devices in either direction. Controllers generally function automatically as a result of **instructions** which are a part of the **operating system.**

core early term for **memory** since **binary** storage units formerly used magnetic technology to determine whether they contained a 0 or a 1.

core resident computer **instructions** which remain in memory at all times so that they provide very rapid execution. Because **memory** is more limited than **mass storage** a compromise is usually achieved between storing **programs** in one site or the other, based on desired performance characteristics.

courseware term used to designate those **application programs,** also called **CBEM,** which have educational objectives. Special purpose, **high-level languages** and **authoring aids** have been developed to facilitate the production of courseware.

Coursewriter III special pupose, **high-level language** developed by IBM to facilitate **CBE.** Coursewriter III is primarily available on **maxi-computers.**

CP/M trademark for a popular **microcomputer operating system** developed by Digital Research, Inc. CP/M can operate on a number of different computers, is able to support a variety of **mass storage** devices, can be used with more than one **computer language,** and therefore facilitates the transfer of **application programs** from one computer to another.

CPU abbreviation for Central Processing Unit. The components of a computer CPU include one or more **registers** for performing arithmetic functions, a **control unit,** and a **memory** unit. The CPU's of large computers are sometimes called mainframes.

CRT abbreviation for Cathode Ray Tube. CRT refers to the screen used in oscilloscopes, television sets, and computer **terminals.** Compare with video **monitor.**

cursor movable indicator on a **CRT.** The cursor is used to identify the position at which the next character typed from the **keyboard** will be displayed.

data acquisition process whereby information derived from analytical instruments (usually in **analog** form) is captured, converted to **digital** form, if necessary, and stored in computer readable form, usually on a **mass storage** device or on magnetic tape.

data base collection of information which is fundamental to a particular effort. Generally, it is implied that this information is available in **computer-readable** form for either **on-line** or **off-line access.** However, some data bases which have been generated by a computer exist only in **hard-copy** form.

data generation automatic creation of numbers by the computer. This can be of particular value, for example, when different sets of numbers may be desired so that individual students can practice statistical analysis on unique but similar data.

data reduction process whereby raw numbers, usually produced by analytical instruments, are converted to refined measurements. Data reduction implies statistical analysis with indications of significant variations from expected outcomes.

debugging see **testing.**

design category of **programming** which involves the way in which a computer **program** is organized to produce the desired solution. Compare with **analysis, coding, testing,** and **implementation.**

digital pertains to the use of numbers and counting to accomplish calculations or information processing. Compare with **analog.**

disk memory see **mass storage.**

diskette circular, flexible medium with magnetic surfaces on which information can be stored for subsequent computer **access.** This medium is one of the least expensive forms of **mass storage.**

diskette drive type of computer **mass storage** device which utilizes a rotating flexible magnetic surface as the storage medium. Information contained on **diskettes** is stored so that any item can be retrieved relatively quickly. Such units are characteristic of moderate-priced **microcomputers** and **terminals.** Compare with **hard-disk drive.**

display screen see **CRT.**

documentation pertains to written information appended to computer **programs** so as to make it easier to understand how they were **designed** or how they are supposed to be **implemented.**

DOS acronym for Disk Operating System, a form of **operating system** which makes use of the **mass storage** capabilities of disks or **diskettes** to provide extended **operating system** capabilities. Compare with **core resident.**

drill and practice those varieties of **CBE** which involve repetitive solutions to simple problems. This approach is used primarily at lower academic levels. Compare with **CMI, CAI** (specific sense), and **simulation.**

edge connectors see **component board** and **slot.**

EPROM see **PROM.**

execution automatic control of a computer which may represent only a few simple **instructions** or the loading of a complex number of routines with

minimal human intervention. See **batch-processing.**

firmware term used to designate **programs** stored in read-only-memory **(ROM).** Ordinarily, firmware cannot be altered. This provides a **hardware** approach to the packaging and marketing of **software.**

floating point notation see **scientific notation.**

floating-point processor arithmetic unit used to perform calculations at high speed. A floating-point processor can be devised either in **hardware** or in **software.**

floppy disk see **diskette.**

FOCAL acronym for Formulating On-line Calculations in Algebraic Language, a general purpose, **high-level language** which is easy to learn and is designed for **interactive** use. FOCAL was originally developed by the Digital Equipment Corporation for use in **minicomputers;** because of its proprietary nature it is not as widely disseminated as **BASIC.**

FORTRAN acronym for FORmula TRANslator, a general purpose, **high-level language** which is especially useful for scientific computing. FORTRAN was originally developed for **batch-processing** but **interactive** versions now exist. FORTRAN is probably the most widely **implemented computer language.**

format pre-determined arrangement of **bits** or characters used either on a **mass storage** medium or in computer **output.**

free text entry ability of an **application program** to accept user **input** without the major restrictions which are required by many **computer languages.** This capability implies that the **application program** includes routines to parse the text, extract its meaning, and branch to an appropriate place in the **program** to meet the user's need.

function generator portion of an **analog computer** which is capable of converting a mathematical expression into simpler terms, usually electrical voltages, resistances, and capacitances, for the purpose of simulating mathematical relationships under conditions which are susceptible to easy manipulation.

graphic ability to plot points, draw lines, or otherwise create pictures either in **hard-copy** or on the **CRT** screen of a computer or a **terminal. Compare with alphanumeric.** More information in definition of **video generator board.**

hard-copy piece of paper on which a computer device has written. This term is used to make a distinction between permanent records and information provided on a **CRT** which is not permanent unless the user makes a record of it. Also refers to **terminals** and **line printers** which generate permanent records **(output).**

hard-disk drive computer **mass storage** device which utilizes rotating platters coated with a magnetic surface for information storage, generally the fastest of the **mass storage** devices. The speed of rotation and the number of read/write heads determine how rapidly information can be **accessed.** Units with multiple platters are used in the largest computers.

hardware category of computer components which involves equipment and excludes the **instructions** to the equipment which are subsumed under the designation **software.** Typically, hardware is divided into two large types: the central processing unit **(CPU)** and **peripheral devices.**

hexadecimal a number system which uses a base of 16 rather than a base of 10 as is used in the conventional (decimal) number system. (The letters A-F are appended beyond 9 to provide the additional single character representations for 10-15.) One hexadecimal digit is capable of representing the information contained in four **binary** digits. Compare with **octal.**

high-level language type of **computer language** which is characterized by: ease of programming, English-like commands, and **implementation** on computers of diverse size and manufacturer. High-level languages may be general purpose such as **BASIC and FORTRAN,** or they may be specialized for particular **computer applications** in the way that **PILOT** and **Coursewriter III** have been developed especially for **CBE.** Compare with **assembly language.**

hybrid computers used to describe computers which have both **analog** and **digital** capabilities. Hybrid computers are relatively unusual, but **analog-to-digital converters** which permit **digital** computers to process **analog** information are widespread.

IC abbreviation for Integrated Circuit.

implementation general sense - the way in which a computer assisted process fits into the overall goals of a human endeavor. Specific sense - category of **programming** which involves the final operation of the **program** in the environment for which it was developed. Compare with **analysis, design, coding,** and **testing.**

in-house computer computer available within an institution. The costs incurred in **assessing** an in-house computer are generally less than using a **service bureau,** unless the machine is underutilized which prevents cost-effective **implementation.**

information representation process whereby information is **coded** before being stored on a computer. Although modifying the representation of the information may save space on the **mass storage** device, it generally complicates the process of **information retrieval** unless the **coding** provides specific means to enhance the retrieval process.

information retrieval process whereby information stored in **memory** or **mass storage** is **accessed,** decoded if necessary, and made available to the user.

initializing process performed at the outset before a substantive task can begin. For example, in an **application program** it may be necessary to reset the values of the **variables** before another set of data can be processed; this is called initializing. Similarly, when first beginning to use a computer, it is necessary to load the **operating system** into **memory** and to request the computer to begin execution at a particular **address.**

input short-hand way of referring to any information, **analog** or **digital,** which is presented to the computer for subsequent processing. Compare with **output.**

instruction written statement, or its equivalent in either **assembly language** or **machine language,** which tells the computer to **execute** a specified single operation. A certain class of instructions called "memory reference instructions" contain the **address** of locations in **memory** which will be altered by the execution of that operation.

integrated circuit electronic unit which combines a single miniaturized component which minimizes power requirements, heat production, and processing time while maximizing reliability. Because of their very small size these units are sometimes called "chips."

integrator component for an **analog computer** which is capable of processing more than one signal and presenting the result in a single combined entity, usually an electrical voltage.

interactive method of maximizing **access** to information contained in **mass storage** by which the user is able to communicate with a **data-base** by way of the computer **console** or a remote computer **terminal.**

interface kind of **computer board** which provides the electronics to permit one portion of the computer to communicate with another. For example, before a **line printer** can be attached to a computer an interface must be present which accepts information as the computer delivers it, and converts it into a form which the **line printer** can use to create **hard-copy.**

K abbreviation for Kilo or thousand (actually, 1,024 or 2 to the 10th power). Used in the designation of the size of **memory** and **mass storage.** For example, many **microprocessors** have as little as 16 K **bytes** of **RAM.**

keyboard element of a computer **terminal** or **console** which enables **alphanumeric** information to be sent to the computer. Most computer keyboards are variants of the standard typewriter keyboard.

language see **assembly language, computer language, high-level language,** and **machine language.**

legal disconnect refers to fulfilling the prescribed procedure for logging-off a **time sharing** computer system, as opposed to merely dropping the telephone connection.

levels of interaction terms used to emphasize that there are hierarchies of **instructions** to the computer. In **interactive** systems, it is possible to be dealing with different portions of the **software**

line printer peripheral device which cases **hard-copy** to be generated by the computer. As the name implies, an entire line is printed at one stroke which permits rapid listing of information.

loading a program process in which the computer places the **binary** version of an **application program** into **memory** prior to requesting execution of that **program.** This is an example of a task **(utility program)** usually performed by an **operating system.**

login requirement process which must be performed in order for a **time-sharing** computer to recognize an authorized user.

LSI abbreviation for Large Scale Integration, see **integrated circuit.**

M abbreviation for Mega or million (actually 1,048,576 or 2 to the 20th power). Used in the designation of the size of **mass storage.** For example, multi-platter **hard disk drives** may have as many as 80 M **bytes** of **mass storage.**

machine code see **machine language.**

machine language representation of information in a form which can be processed by the computer. Machine language consists entirely of **binary** representation, hence only the number 0 and 1 are used. Such representation is generally uncomprehensible to human beings. Each individual computer model has a unique machine language. The **object** generated from an **assembly language** source is in machine language which is sometimes also called machine code.

magtape acronym for magnetic tape; generally refers to ½" magnetic tape with storage at 800 and 1600 **bits** per inch. This size has become an industry standard for medium-sized and larger computers. Storage on magtape is referred to as **off-line** storage when the magtape is not mounted on an active tape drive connected to the computer.

mainframe see **CPU.**

mass storage term used to refer to a secondary, **on-line** repository for **data bases** and **application programs. Access** is not as rapid as from computer **memory,** but mass storage is more economical than storage in **memory.** Typically, mass storage occurs on **diskette drives** in **microcomputers** and on **hard-disk drives** in larger machines.

maxi-computer largest category of computers. Maxi-computers tend to be very fast, have large amounts of **mass storage,** and accommodate many tasks at the same time. They are very expensive, generally in excess of $1,000,000.

megabyte see **M.**

memory organized collection of storage elements in the **CPU** of a computer into which **instructions** and data consisting of **binary** digits can be deposited and from which information can be retrieved. Compare with **mass storage** and **off-line storage.**

microcomputer smallest category of computers. Microcomputers tend to be miniaturized, are often dedicated to performing simple tasks, and do not usually have much flexibility. Wrist watches and hand-held calculators are examples of one end of the scale. Personal computers which cost $10,000 or less represent the upper cost limit of these devices.

midicomputer medium scale computers which represent an intermediate between **maxicomputers** and **minicomputers** both in terms of processing power and cost. Midicomputers range in cost from $100,000 to $1,000,000.

minicomputer category of computers representing the original effort, circa 1960, to offer smaller computers at a lower cost. Early machines in this category cost about $25,000. They continued to become less expensive, but now that this effort has created **microcomputers,** minicomputers encompass a range of cost from approximately $10,000 to $100,000.

minifloppy disk drive smaller version of the **diskette drive.** Standard **diskettes** are 8" in diameter and when recorded on one surface in single density **format** contain 256,000 **bytes** of storage. Minifloppy **diskettes** are 5¼" in diameter and when recorded on one surface in single density **format** contain approximately 100,000 **bytes** of storage.

model in a computer **simulation,** this refers to the conceptualization of the program prior to attempting to **program** the **simulation.** Frequently, models are couched as a series of mathematical relationships or equations. In describing **hardware,** the word model refers to a particular version of the equipment.

MOS acronym for Metal Oxide Semiconductor electronic **memory** which has replaced the earlier magnetic **memory (core).**

motherboard principle component of a **microcomputer** which contains the power supply, the **bus,** and a front panel which may have indicators and controls that constitute a computer **console. Component boards** are installed on the **bus** to give a particular **microcomputer** its desired capabilities.

multiplier component of an **analog computer** which is capable of multiplying two signals together and presenting the product in a single entity, usually an electrical voltage.

network collection of computers, communication links, and telephone lines which make it possible for a user to communicate with one or more **remote computers** without having to pay prohibitive long distance telephone charges. A user needs a computer **terminal** and an **interface** to the telephone system in order to **access** a **remote computer.**

object **binary** form of an **assembly language program** which is created by the assembler. It consists of 0's and 1's and can be directly **executed** by the computer.

octal pertains to a number system which uses a base of 8 rather than a base of 10 as in the conventional (decimal) number system. Octal uses only the digits 0 through 7. One octal digit provides a convenient numerical representation for the information contained in three **binary** digits. Compare with **hexadecimal.**

off-line information stored in computer-readable form (punched cards, punched paper tape, **magtape, diskettes,** or disks) but not currently in the computer and therefore unavailable for direct **access.** Compare with **on-line.**

on-line information currently in an active **mass storage** device and therefore available for direct **access.** Compare with **off-line.**

operating system category of **software** which includes **utility programs** that automatically perform sequences of tasks which would be tedious for a human operator. Compare with **computer language** and **application program.**

operational amplifier component of an **analog computer** which not only amplifies a signal but also performs some operation, such as reversing the sign, or taking a derivative of the signal.

OS/8 abbreviation for the device independent, **operating system** for the Digital Equipment Corporation PDP-8 **minicomputer.** Device independent means that PDP-8's with different amounts of **memory** or **mass-storage,** and different complements of **peripheral devices** can all be using a standard **programming** environment which facilitates the transportability of **programs** from one machine to another.

output short-hand way of referring to any information, presented on a **CRT** or in **hard-copy,** which is the result of the computer following a set of **instructions** or an **application program.** Compare with **input.**

parity check process whereby transfers of information within the computer are checked for the occurrence of the same number of **binary** 1's in each **computer word** transferred. **Memory** which has parity checking built-in, will require one more **bit** than the length of the **computer word** for that **CPU.**

patch panel component of an **analog computer** which simplifies converting the problem into an electrical analog (essentially to **program** the **analog computer**) by plugging in wires from one component of the **analog computer** to another as indicated on the patch panel.

performance enhancer see **arithmetic processor board** and **floating-point processor.**

peripheral device type of computer **hardware** which includes all electronic and electro-mechanical

devices which can be attached to the computer except those subsumed under the designation **CPU**. Examples include **line-printers, hard-disk drives, interfaces** to the telephone system, etc.

personal computer term used to describe either a **microcomputer** or a **minicomputer**, which is intended for use by only one person. Personal computers which have an **interface** to the telephone system may also be used as computer **terminals** to larger machines.

pin assignments refers to multiple connectors in computer **buses, component boards**, plugs or sockets and the signals assigned to each connector. Often devices which are physically compatible because they have the same number and arrangement of connectors, become incompatible when the signal lines are not assigned to the same connectors.

plotting capability the ability of a **CRT** or a **hard-copy** device to produce **graphic output.**

pot abbreviation for potentiometer, a variable electrical resistance. Pots are used in **analog computers** to change the conditions of the problem.

power supply component of a **motherboard** which converts conventional electricity (110 volt, 60 cycle AC) into DC voltages. These are used to operate modern electronic units mounted on **component boards** and plugged into the **bus.**

printer see **line printer.**

program collection of **instructions** to a computer. More information in definition of **programming.** Programs for **digital** computers are written in **computer languages.** Programs for **analog computers** consist of equations and diagrams that indicate the **analog** operators which will be used to arrive at the solution.

programming total process of developing solutions to the problems contained in **computer applications.** Programming involves the following steps: **analysis, design, coding, testing,** and **implementation.**

programming aid see **authoring aid.**

PROM acronym for Programmable Read Only Memory. As originally developed, **ROM** could not be altered once it had been created. PROM was the first step in improved flexibility in **firmware.** Subsequently, **memory** was constructed in **integrated circuits** whose contents could be erased (EPROM) with ultraviolet light and then reprogrammed.

RAM acronym for Random Access Memory, computer **memory** which consists of electronic units and is capable of having its contents changed. More information in the definitions of **memory** and **ROM.**

random-access storage see **mass storage.**

real-time clock peripheral device which enables the computer to keep time in human dimensions, i.e., seconds, minutes, hours, days, months, and years. Real-time clocks tick at relatively high speed and must be supported by **application programs** to convert this information into real-time.

register component of a **CPU.** This electronic device is able to retain as many **bits** of information as are present in the **computer word** of the particular machine. Arithmetic functions and evaluations (whether the register contains 0 or a negative or a positive number) must be performed in registers. The latter are also used to store intermediate values in certain calculations or retrieval operations.

remote computer a computer which is not located at the site of **access.** The term implies that such a machine can be **accessed** by way of the telephone system and a computer **terminal.**

resolution term used to describe the capability of a **video monitor** to display pictures **(graphics).** The higher the resolution the more detail is visible in the ultimate screen image.

ROM abbreviation for Read Only Memory. Describes computer **memory** whose contents can be read but cannot be altered. Compare with **RAM.**

S-100 bus a unitized **bus** for **microcomputers** based on either the Intel 8080 or the Zylog Z-80 **integrated circuit.** Several different manufacturers have developed **component boards** for the S-100 bus, therefore it has become a "standard" **bus** for these popular **microcomputers.**

scientific notation method of expressing numbers in compact form in which the integer and exponent portions of the number are separately represented. This notation is used to enhance the speed of a **floating point processor.**

semiconductor memory see **MOS.**

service bureau source of computer services on a commercial basis. Compare with **in-house computer.**

simulation a variety of **CBE** which involves developing a computer **model** of a human activity in order to be able to learn more about that activity. Compare with **drill and practice, CMI** and **CAI** (specific sense).

slot a position on a unitized **bus** where a **component board** can be installed. Typically, there are 10-40 slots on a bus, but it is generally possible to extend the **bus,** to another unit with additional slots. The **component board** is positioned on the bus by inserting the "edge connectors" in the slot.

software category of computer components which is restricted to **instructions** to the equipment **(hardware).** Typically, software can be divided into **operating systems, computer languages,** and **application programs.**

solid state memory see **MOS**

source see **assembly language** and **machine language**

special purpose board one of several types of **component boards** which carry out such functions as improving the speed of calculations **(arithmetic**

processor board or **floating point processor**) or enabling the conversion of **analog** signals to **digital** format.

tape memory see **magtape**

television see **video technology**

terminal **peripheral device** which enables a user to **interact** with a computer. Computer terminals consist of three elements: a **keyboard**, either a display screen (**CRT**) or a **hard-copy** unit, and an **interface** which connects the terminal to the computer directly or, indirectly, through the telephone network.

testing category of **programming** involves identifying errors in **computer language** syntax, flaws in logic, and other impediments to the operation of a computer program. This process is also called "debugging."

time-sharing method of maximizing the utilization of computers in which more than one user is able to share the computer by having the **operating system** provide each user in sequence an allotted increment of computer time. Compare with **batch-processing.**

transportability extent to which **courseware** and other **application programs** can be transferred from one computer to another without having to rewrite the **program.**

turn-around time in a **batch-processing** environment the time between submitting a job request and the receipt of the **output.**

unitized see **bus**

user memory partition allocation of **memory** which permits more than one user to have **interactive access** to a computer running under **time-sharing.**

utility program sub-unit of an **operating system** which performs repetitive tasks without requiring human intervention.

variable term used in **programming** to refer to a particular symbol, such as the letter x, which may take on one value at one point in time and another value at a different point in time.

video generator board a **component board** of the category of **interfaces** which creates a screen display for delivery to a **video monitor.** Relatively primitive video generator boards determine the number of lines to be displayed, the number of characters per line, and the character set (usually **alphanumeric**). More advanced equipment permits **graphics,** variation of intensity, and even color displays.

video interface see **video generator board**

video monitor screen used in computer **terminals** where the display is based on **video technology.** A video monitor contains all the components of a television set except those which make it possible to receive broadcast television programs.

video technology pertains to **hardware** devices which make use of the developments created for and by the television industry.

APPENDIX

Techniques Used to Develop the Glossary and the Basic Vocabulary

The manuscripts comprising this volume were scanned by a person not familiar with computer technology who highlighted every term which might be considered to be technical in nature. The appropriate terms from this list were transferred to 4"x6" cards and alphabetized. Definitions were developed for these terms making frequent use of other terms from the Glossary so that users would perceive the context in which computer terms are used. A number of new terms were introduced to provide a sufficiently broad context and to assure that an adequate subset of computer jargon was available.

The entire list of definitions were then reviewed by Katharine C. Donovan, a second volunteer without previous computer exposure. In addition to providing stylistic integrity, Mrs. Donovan made sure that every definition would impart some meaning to those not previously knowledgeable on the subject.

The Basic Vocabulary was determined by performing an item analysis on the Glossary and observing the frequency of use for the most popular terms as they appeared in the definitions. From an initial list of approximately 40 terms, the final list was refined by determining the smallest subset of terms which would create the simplest exposure to computer terminology. The three references which follow are aknowledged as sources of glossary style and content information.

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INDEX*

Accreditations and standards
  American National Standards Institution (ANSI), 32, *48*
  American Standard Code for Information Interchange (ASCII), *48*
Analog computer: *see* Computers, analog
Analog-digital converter: *see* Computers, analog
Analysis: *see* Programming
ANSI: *see* Accreditations and standards
APL: *see* Computer languages
Application programs: *see also* Authoring aid; Computer-assisted instruction; Simulations
  3, 9–10, *48*
ASCII: *see* Accreditations and standards
Assembly language: *see* Computer languages
Assessment of simulations: *see* Simulations
Authoring aid
  48
  MACAID program, 42

BASIC: *see* Computer languages
Batch processing: *see* Styles of computer utilization
Binary language: *see* Computer languages
Bus: *see* Computer hardware

CAI: *see* Computer-based education
CASE: *see* Simulations
Central processing unit: *see also* Memory
  3, 8, 10, 45, *49*, *50*
  arithmetic unit, 8, 9,
  control unit, 8, 9, *50*
  floating-point processor, 25, *51*
  register, 4, 8–9, *54*
CMI: *see* Computer-based education
COBOL: *see* Computer languages
Coding: *see* Programming
Computer-assisted instruction (CAI): *see* Computer-based education
Computer-based education (CBE): *see also* Simulations
  10, 12–13, 15–19, 21–23, 23–26, 27–33, 33–36, 37–42, 43–46, *49*
  computer-assisted instruction (CAI), definition of, *49*
  computer-managed instruction (CMI), *49*
  drill and practice, *50*
  free text entry in, *51*
  in teaching of physiology, 10, 15–19, 21–23, 23–26, 27–33, 33–36, 37–42, 43–46
  program at George Washington University Medical Center, 18
Computer-based educational materials (CBEM): *see* Courseware
Computer games
  15, 16–17, *49*
  ROCKET simulation program, 15, 16–17

* Page numbers in italics refer to terms that appear in the glossary.

Computer hardware: *see also* Central processing unit; Peripheral devices
AM-9511 processor board, 25–26, *48*
analog-digital interface, 22
analog-to-digital converter, 22, 33, *48*
arithmetic processor board, 25–26, *48*
bus, 23, 26, *49*
card, *49*
cathode-ray tube (CRT), 2, 3, *50*
chip, *49*
component board, 23, 26, 36, *49*
configuration, 23, 26, 33, 34, 35–36, *49*
controller, *50*
definition of, 2–3, 4, 10, 13, 23–24, *51*
display screen, *50*
edge connectors, *51*
firmware, *51*
historical aspects, 4
integrated circuit, 4, 7, *52*
motherboard, 26, *53*
performance enhancer, 25–26, *53*
pin assignments, *54*
personal computers, 22–26, 27–33, *53*
plotting capability, *54*
power supply, *54*
real-time clock, *54*
S-100 bus, 23, 26, *54*
slot, 26, *54*
special-purpose board, *54*
Computer languages
2, 3, 9, *49*
APL, 9, *48*
assembly language, 9, *48*
BASIC, 9, 24, 25, 26, 33, 36, *48*
binary language, 2, 3, 8, 9, 25, *52*
COBOL, 9, *49*
Coursewriter III, *50*
FOCAL, 9, *51*
FORTRAN, 2, 9, 24, 26, 33, 34, 36, *51*
high-level language, 3, 9, 25, 33, *51*
machine language, 2, 3, 8, 9, 25, *52*
Microsoft BASIC, 26
Computer software: *see also* Application programs; Computer languages; Operating systems; Programming
computer-readable programs, *49*
core resident, *50*
definition of, 2, 3, 9, *54*
execution, 9, 10, 33
instruction, 3, *52*
levels of interaction, 9–10
loading a program, *52*
object, *53*
program, definition of, 2, 3, 9–10, 15, *54*
programs available from Biomedical Communication Network, 11
source program, 9, *54*
transportability of, 9, *55*
Computers
access to stored data, 3, 5, 7, 11, 15, 19, *48*
alphanumeric notation, *48*
basic vocabulary, 47
baud unit of transmission rate, *48*
binary coded decimal (BCD), 25, *48*
binary number system, 2, 3, 4, 8, 9, *48*
bit, 4, 8, *48*
bytes, 4, 8, *49*
computer application, 2, 4, 5, 7, 10, *49*
computer literacy, 5, *49*
computer word, 4, 8, *49*
data generation, *50*
data reduction, *50*
digital notation, *50*
execution of tasks, 3, *51*
floating-point notation, *51*
format, *51*
glossary, 47–55
hexadecimal number system, 8, *51*
history of, 4
how to become involved in use of, 11
hybrid computers, *51*
in-house computer, *51*
in teaching of physiology, 5, 15–19
information representation in, 8–9, *51*
information retrieval capabilities of, 7
initializing, *52*
input, *52*
legal disconnect, *52*
login requirement, 41, *52*
maxicomputer, 4, *52*
medical applications of, 7, 10–11
microcomputer, 3, 4, 5, 23, 26, 27–33, 35, *53*
midicomputer, 4, *53*
minicomputer, 4, 33–36, *53*
number representation for sequences of zeros and ones in, 8
octal and hexadecimal number systems, 8
octal number system, 8, *53*
off-line storage, *53*
on-line storage, *53*
output, *53*
output and its format, 5
parity check, 7, *53*
personal computer, 23–26, 27–33, *53*
personal computers, use in teaching by simulation, 23–26, 27–33
plotting capability, *54*
precision of, 7
primer on technology of, 7–11
pros and cons of analog computer in relation to digital computer, 12–13
reliability of, 10
remote computer, 10, *54*
sample sequence of events for simple task, 8–9
scientific notation, *54*
service bureau, *54*
size of, 4, 10
speed of, 7
storage capability of, 7–8
terminology of, 2–3, 10, 47–55
turn-around time, *55*
Computers, analog
analog data, *48*
analog-digital interface, 22
analog-to-digital converter, 22, 33, 34, *48*
definition of, 2–3, 12–13, *48*
electronic circuits in, 13
example of use in studying CO_2 control in respiratory system, 21–22
example of use in studying respiratory control function, 14

function generator, 13, *51*
hardware requirements for teaching physiology courses, 22–23
hybrid computers, *51*
in teaching of physiology, 12–14, 21–23
integrator, 13, *52*
multiplier, 13, *53*
operational amplifier, 13, *53*
patch panel, 13, *53*
pot (potentiometer), 13, *54*
pros and cons in relation to digital computers, 12–13
Computers, digital: *see* Computers
Console: *see* Peripheral devices
Core: *see* Memory
Courseware
15, 16, *50*
Acid Base CHEMistry, 15
ACId BAse chemistry, 15
computer-based education mat ials (CEBM), 11, 15, 37–42, *49*
TERMLEARN, 15, 16
transportability of, *55*
tutorials, 15
CP/M: *see* Operating systems
CPR: *see* Simulations
CPU: *see* Central processing unit

Debugging: *see* Programming
Design: *see* Programming
Diskette: *see* Mass storage
Documentation
42, 45, 46, *50*
for MAC models, 42
DOS: *see* Operating systems

EPROM: *see* Memory
Ethics, medical
in research, fostering in physiology students, 1

FOCAL: *see* Computer languages
FORTRAN: *see* Computer languages
Function generator: *see* Computers, analog

Graphic displays: *see* Peripheral devices

High-level languages: *see* Computer languages

Implementation: *see* Programming
Information storage and retrieval
Biomedical Communication Network of Lister Hill Center, 10, 11
computer-readable data, *49*
data acquisition, *50*
data base, *50*
Health Education Network, Inc., 15
information representation in digital computers, 8–9, *51*
information retrieval process, *52*
input, *52*
institutions in Biomedical Communication Network, 11
MEDLINE system, 11
network, 10, 19, *53*
use of computers in, 7
Input devices: *see* Peripheral devices
Interactive computing: *see* Styles of computer utilization
Interfaces: *see* Peripheral devices

Keyboard: *see* Peripheral devices

Line printer: *see* Peripheral devices

MAC family of computer simulations: *see* Simulations
Machine language: *see* Computer languages
Magnetic core: *see* Memory
Mainframe: *see* Central processing unit
Mass storage
3, 4, 8, 23, 24, 26, *52*
cassette drive, *49*
disk memory, 8
diskette, *50*
floppy disks, 24, 26, *51*
hard-disk drive, *51*
M notation of size, 4, *52*
magnetic tape memory, 8
magtape, *52*
megabytes, 4, *52*
minifloppy-disk drive, *53*
on-line storage, *53*
Medical research
ethics of, fostering in physiology students, 1
Medicine
application of computer technology in, 7, 10–11
Memory
3, 4, 7–8, 9, 24, 26, *52*
address in memory, *48*
core, *50*
EPROM, *51*
K notation of size, 4, *52*
M notation of size, 4, *52*
MOS, *53*
PROM, *54*
RAM (random access memory), *54*
ROM, *54*
semiconductor memory, *54*
solid-state memory, *54*
user memory partition, *55*
Model: *see* Simulations
MOS: *see* Memory

Network: *see* Information storage and retrieval

Operating systems
3, 9, 10, *53*
CP/M, 26, *50*
disk-operating system (DOS), 26, *50*
OS/8, 33, *53*
utility program, *55*
Operational amplifier: *see* Computers, analog
OS/8: *see Operating systems*

Peripheral devices: *see also* Mass storage, Video technology
3, 8, *53*
console, *50*
graphic displays, 23, 24, 25, 26, *51*
hard-copy output, 23, *51*
input devices, 8, 9
interface, 25, 26, *52*
keyboard, 3, 5, 10, 11, 15, 16, 19, 23, 26, 33, 34, *52*
line printer, *52*
output device, 5

printer, 23, *54*
terminals, 3, 5, 10, 11, 15, 16, 19, 23, 26, 33, 34, 36, 41, *54*
Personal computer: *see* Computers
Physiology
analog computers in teaching of, 12–14, 21–23
computer simulation in student laboratory, 33–36
computer simulations, advantages of, 43–44
computer simulations, evaluation of, 44–45
computer simulations in teaching, 15–19, 23–26, 27–33, 37–42
computer simulations, limitations of, 45–46
computer simulations with personal computers, 23–26
laboratory exercises in teaching of, 1–2
student exposure to medical procedures, 2
student introduction to biological variation, 2
student introduction to ethics of medical research, 1
student observation of characteristics of living material, 1–2
Printers: *see* Peripheral devices
Programming: *see also* Computer software; Documentation
analysis process, *48*
application programming, 10
authoring aid, *48*
coding, *49*
debugging, *50*
definition of, 3, *54*
design, *50*
implementation, 27, 33, *51*
simulation programming, 43, 44, 45
testing, *55*
variable, *55*
Programs: *see* Computer software
PROM: *see* Memory

RAM: *see* Memory
Random-access storage: *see* Mass storage
ROCKET: *see* Computer games
ROM: *see* Memory

S-100 bus: *see* Computer hardware
Simulations
5, 10, 15, 16, 17–19, 23, 25–26, 27–33, 33–36, 37–42, 43–46, *54*
action-potential simulation on personal computers, 24–26
cardiopulmonary resuscitation (CPR) simulation program, 15, 18
CELLMBrane simulation program, 15, 16, 17
CO_2 control in respiratory system, 14, 21–22
computer aided simulation of the clinical encounter (CASE), 15, 19
diabetic ketoacidosis (DKA) simulation program, 15, 18–19
graphic display of action potential simulation on personal computers, 25–26
Hodgkin-Huxley simulation program, 24, 26
in respiratory control function, 14, 21–22
MACBABE simulation program, 42
MACDIVE simulation program, 42
MACDOPE simulation program, 42
MACMAN simulation program, 15, 16, 17, 18, 37, 42
MACPEE simulation program, 15, 17, 18, 37–42
MACPUF simulation program, 15, 17–18, 42
model in, 14, 18, 21, 27–33, 33–36, 37–42, *53*
model of cardiovascular system for effective learning, 27–33, 33–36, 37–42
model of renal physiology, 37–42
physiological simulations, advantages of, 43–44
physiological simulations, evaluation of, 44–45
physiological simulations, limitations of, 45–46
ROCKET simulation program, 16
Styles of computer utilization
batch processing, 4, 5, 9, 10, 16, *48*
interactive computing, 10, 15, 16, 19, 27, *52*
levels of interaction, 9–10, *52*
major categories of utilization, 9
time sharing, 5, 9, 10, 27, 37, *55*

Terminals: *see* Peripheral devices
TERMLEARN: *see* Courseware
Testing: *see* Programming
Time sharing: *see* Styles of computer utilization

Utility programs: *see* Operating systems

Video technology
16, 23–24, 30, 36, 38, *55*
cursor, *50*
graphic displays, 23, 24, 25, 26, *51*
resolution of video monitor, *54*
video generator board, *55*
video monitor, 23, 26, *55*

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